ADVANCED NOISE CONTROL FAN
A 20-Year Retrospective

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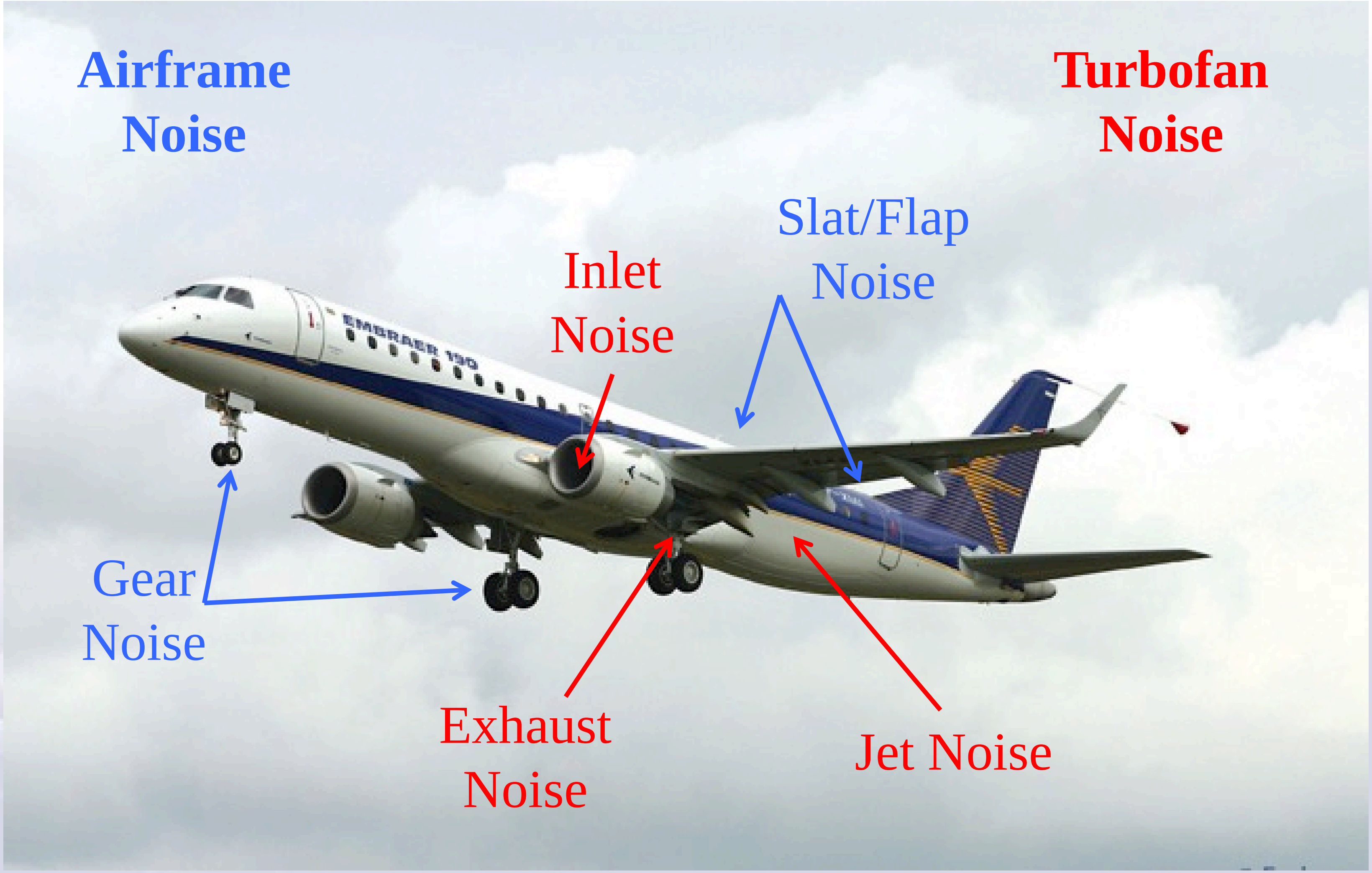
BACKGROUND

Sources of Aircraft Noise

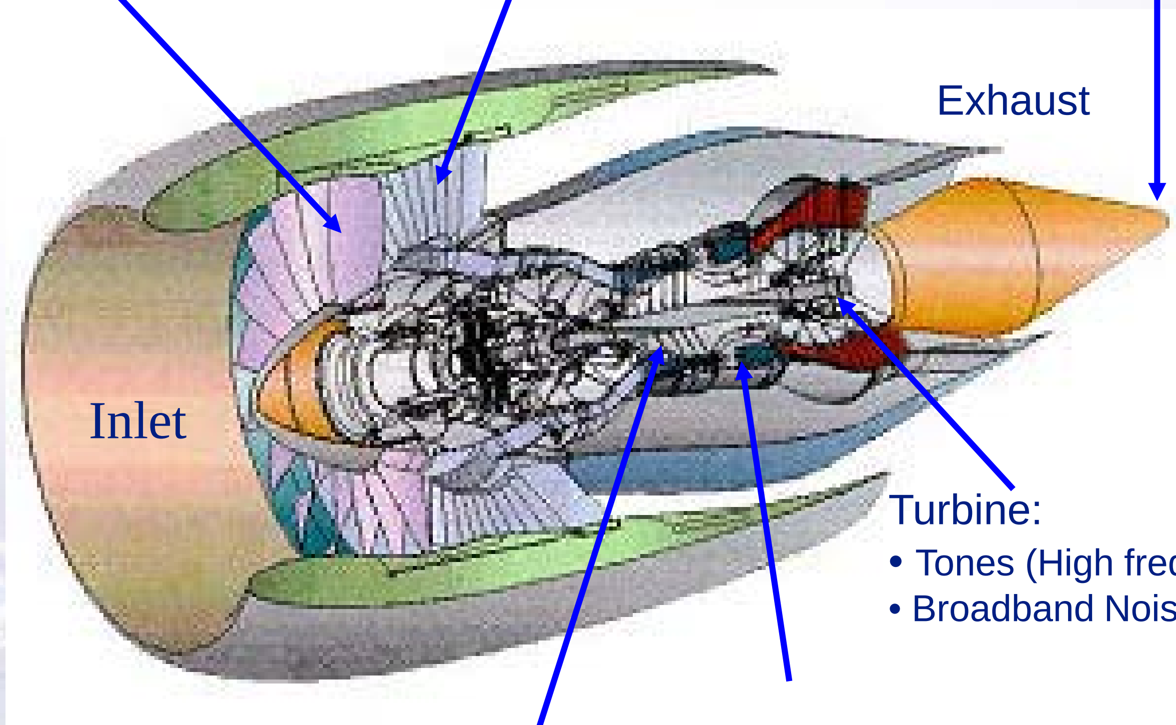


Sources of Turbofan Engine Noise

Fan:
- Tones (harmonics)
- Broadband Noise
- “Buzz-Saw” Noise

Stator:
- Tones (harmonics)
- Broadband Noise
- Duct-modes

Jet:
- Broadband Noise (Low frequency)
- Distributed



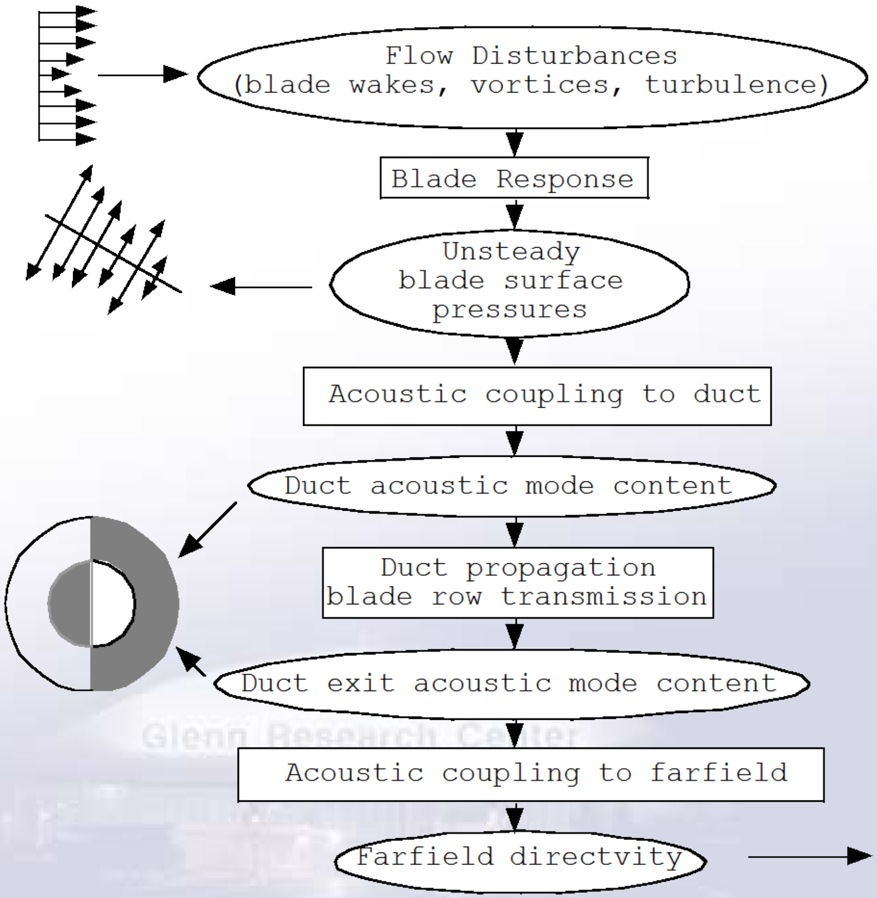
Turbine:
- Tones (High frequency)
- Broadband Noise (High frequency)

Compressor:
- Tones (High frequency)
- Broadband Noise

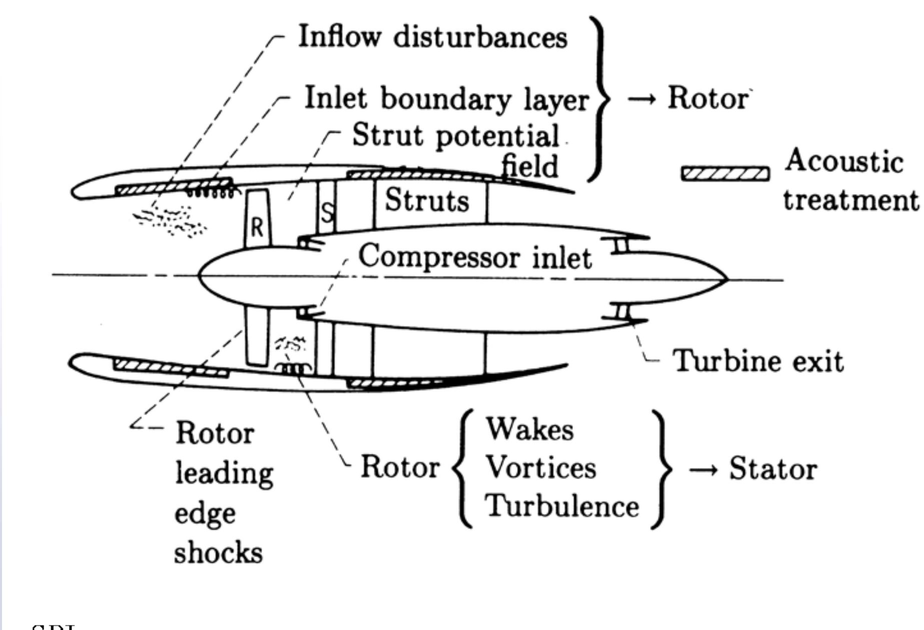
Combustor:
- Broadband Noise (Low frequency)

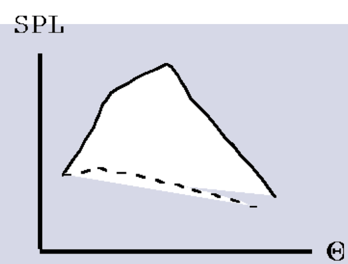
Aircraft Engine Noise

Acoustic Generation



Engine Schematic





OVALS:
Physically measure-able quantity

RECTANGLES:
Physics/cause & effect

OVERVIEW

Advanced (nee: Active) Noise Control Fan

ANCF is located in AeroAcoustic Propulsion Laboratory at NASA Glenn Research Center

65' radius anechoic dome for acoustic and other measurements (Anechoic to 125 Hz.)

Cooper, B.A., "A Large Hemi-Anechoic Chamber Enclosure for Community-Compatible Aeroacoustic Testing of Aircraft Propulsion Systems", Journal of the Institute of Noise Control Engineering of the USA, Jan/Feb 1994.

Originally built as part of the AST/QAT engine noise reduction program in ~ 1992.

Initial Operation in 1994 / 1995

Highly flexible, fundamental test bed.

Can test multiple configurations, including rotor alone.

4-foot diameter ducted fan - 75 HP electric motor

Low speed: (variable)

Ω=1886 rpm, V_{tip} ~400 ft/sec, M_{duct} ~ 0.14

Used to evaluate *active* noise control technologies and develop a duct mode database.

In early 2000's upgraded to 200 HP motor:

Ω=2500 rpm, V_{tip} ~525 ft/sec,

Renamed to Advanced Noise Control Fan when research emphasis changed.

1995	2000	2005	2010	2015
Active Noise Control		Unique Fan Noise Reduction Techniques		Novel Liner develop
			Array development / Rotating Rake enhancement	

Advanced Noise Control Fan

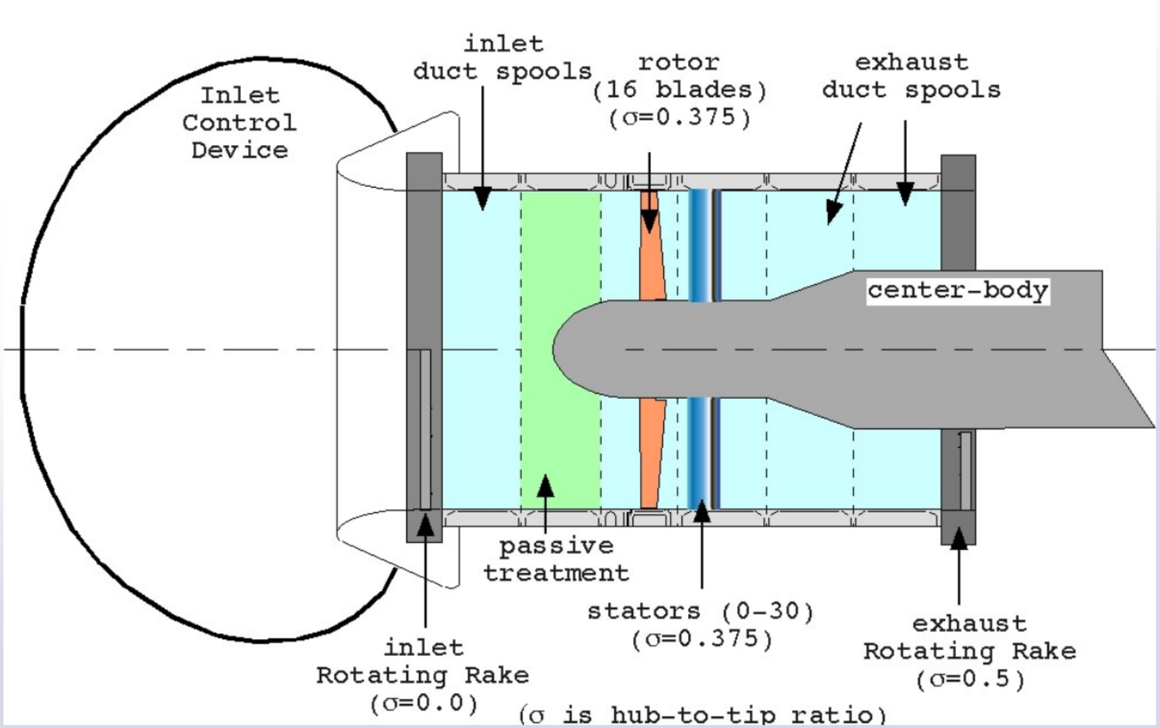
ICD for flow conditioning.

Spool pieces can be configured and rearranged (e.g. install microphones, pressure taps) or replaced with specialized spool.

Center-body is also configurable and available for instrumentation.

Location of traverse mechanism (PACS) can be varied:

(hotwire, Kiel or Static pressure probes)



16 Rotor blades mounted on hub
- 5.25” chord, ~ 15” span
- variable pitch (18°, **28°**, 38°)

26/28/30 count stator vane hubs
- 4.5” chord, ~ 15” span
- variable spacing (typically 0.5, 1.0, 2.0 C)

ANCF Test Bed Measurement Locations

ICD for flow conditioning.

Spool pieces can be configured and rearranged (e.g. install microphones, pressure taps) or replaced with specialized spool.

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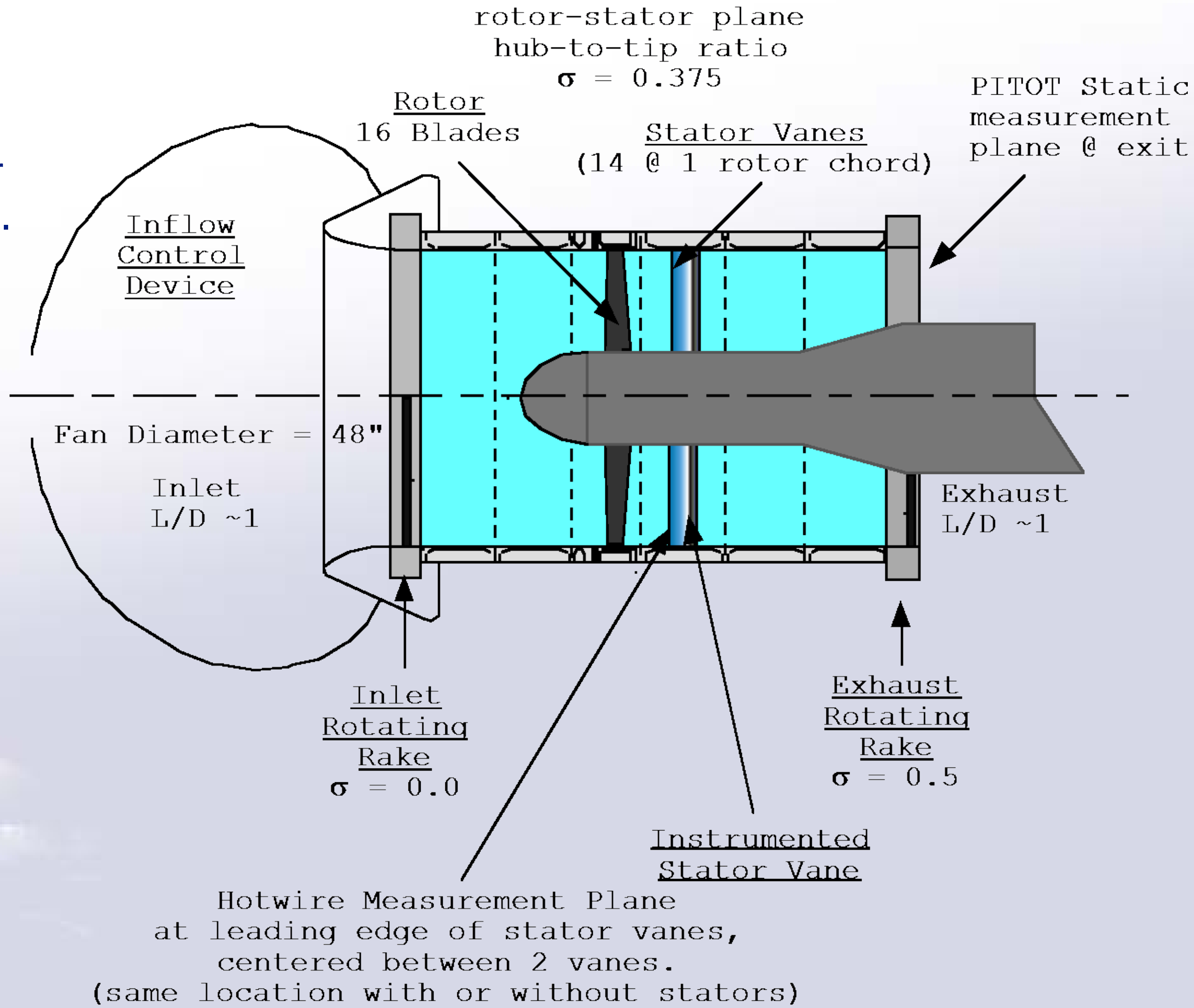


Measurement Capabilities

- In-Duct Mode Levels (RR)
- Rotor Wakes (HW)
- Stator Vane Pressures
- Duct Wall Pressures
- Farfield Directivity

Data Acquisition Systems

Typical Measurements:

- Farfield; Rotating Rake (unique in-duct mode measurements)
- Hot-film; Dynamic & Static Pressure; Mounted Microphone

Probe measurements can be radially/circumferentially traversed.

3x32 channel Nicolet Odyssey Data Recorder.

- 100 Ksamples/sec sample rate (50 kHz if externally sampled)

16 channel Nicolet Odyssey High Speed Data Recorder.

- 10 Msamples/sec sample rate (1 Msamples/sec if externally sampled)

2-channel Dantec CTA w/ flow calibrator (expandable to 4 ch).

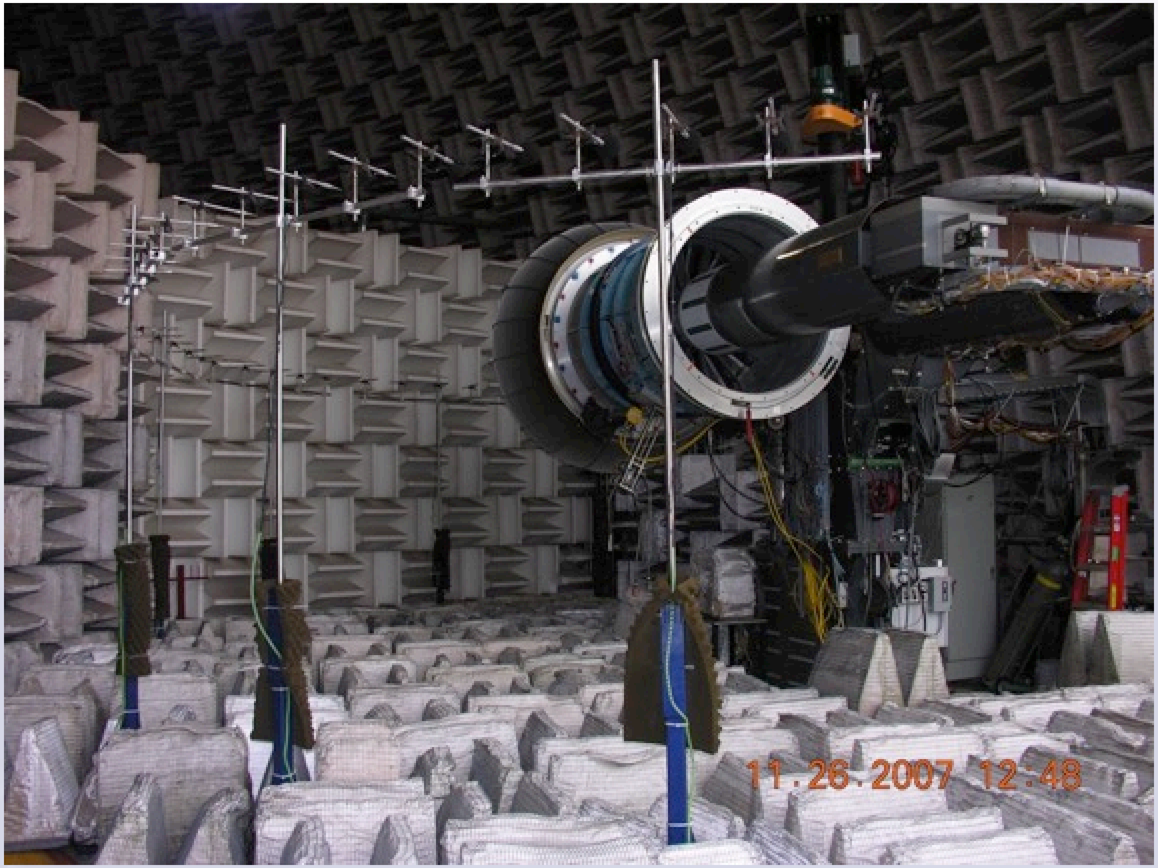
ESP/ESCORT data systems for steady state measurements.

Compact Farfield Arena

Enclosed compact farfield arena for continuous usage.

30 Farfield microphones

- Piezotronics 130D20 ‘array’ microphones
- 10 KHz best range
- 6 stands of 5 mics
- 15 fwd/15 aft arcs @ 12’ radius/10’ height

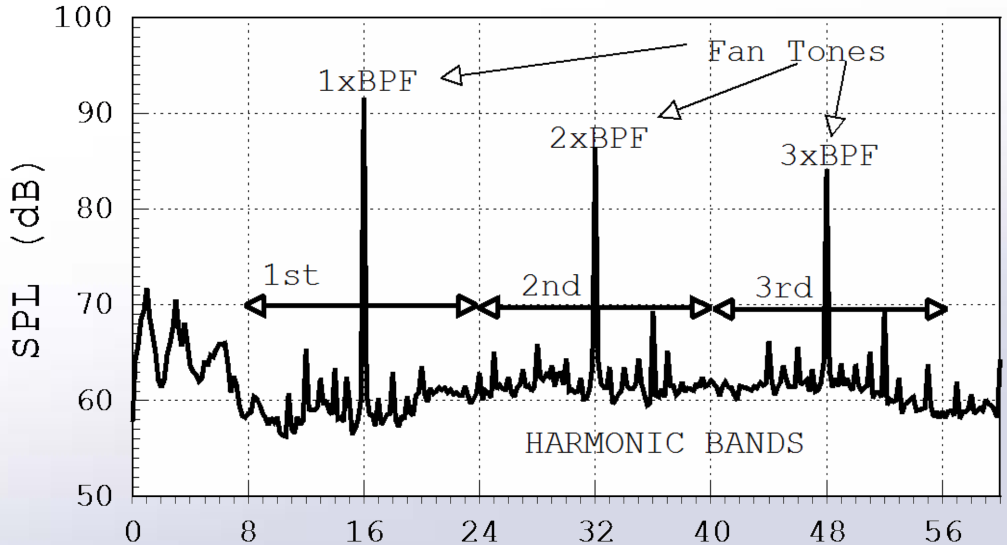


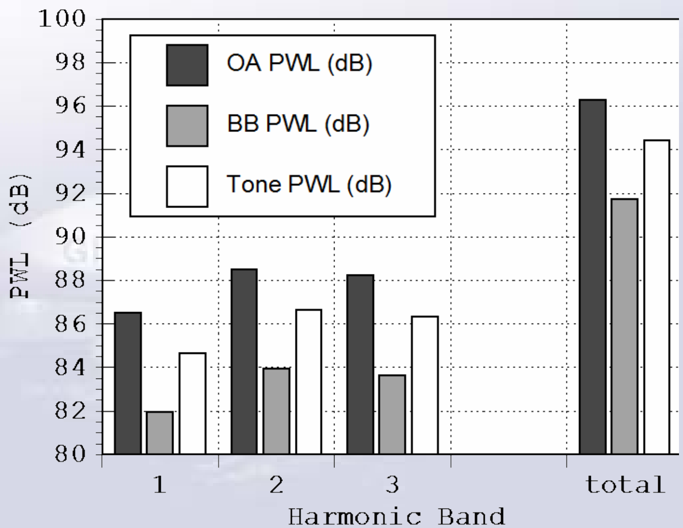
Dynamic Data Reduction

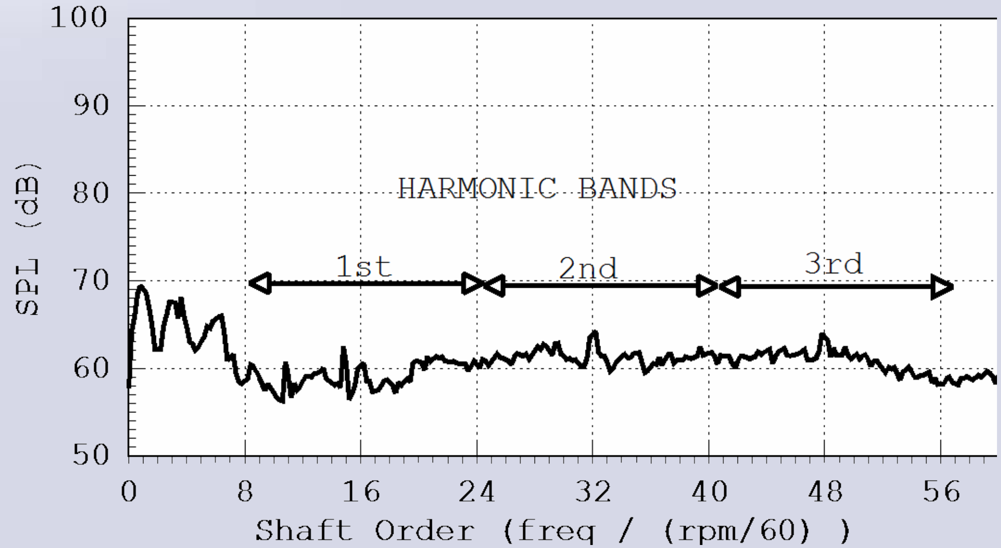
- Data acquired synchronously sampled to fan shaft @ 128/rev
- Frequency/time domain averaged
- Spectra for each microphone integrated over ‘harmonic bands’

  i.e. $^{1}/_{2}$ to $1^{1}/_{2}$ harmonics
  or 8 to 24 shaft orders (etc)

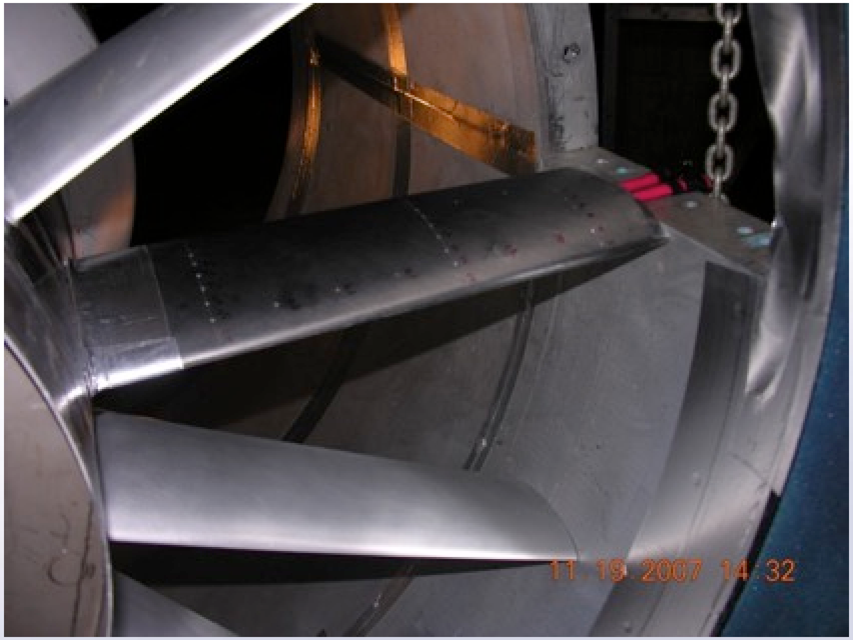
multiplied by area, etc, to obtain PWL
- Overall/Broadband/Tones







Internal Acoustics



Internal acoustics measured by Rotating Rake*

Continuously rotating, radially distributed from tip to hub array of pressure transducers installed at inlet/exhaust duct acoustic release point.

A complete circumferential and radial modal magnitude & phase map is obtained for the 1st three harmonics.

Carbon fiber vane with embedded/flush mounted microphones for measuring vane surface dynamic pressures.

- 30 per side
- 20% leading edge line
- 3 chord lines

Used to determine response of stator vane to rotor viscous wake.

∗Sutliff, D.L. “Rotating Rake Turbofan Duct Mode Measurement System” NASA TM-2005-213828, November 2005.

Summary

The ANCF test bed is used for evaluating fan noise reduction concepts, developing noise measurement technologies, and providing a database for Aero-acoustic code development.

Rig Capabilities:

- 4 foot 16 bladed rotor @ 2500 rpm
- Auxiliary air delivery system 3 lbm/sec @ 6/12 psi)
- Variable configuration (rotor pitch angle, stator count/position, duct length)
- synthetic acoustic noise generation (tone/broadband)

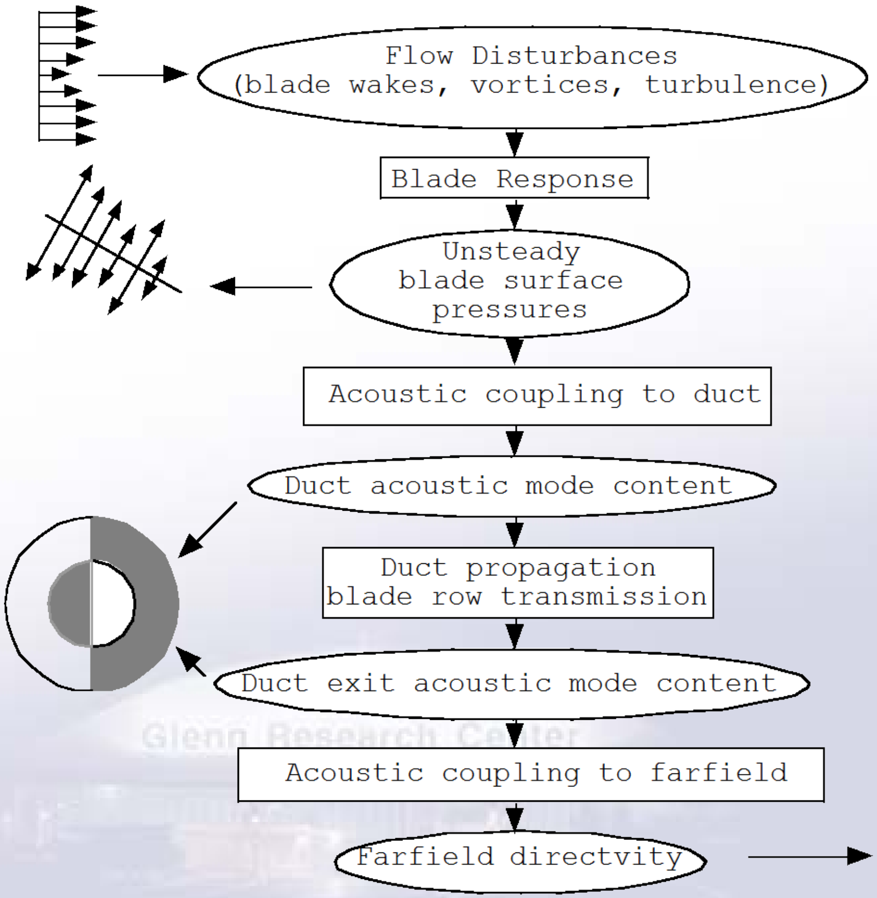
Measurement Capabilities:

- 112 channels dynamic data system
- Unique rotating rake mode measurement
- Farfield (variable radius)
- Duct wall microphones
- Stator vane microphones
- Two component CTA w/ traversing
- ESP for static pressures

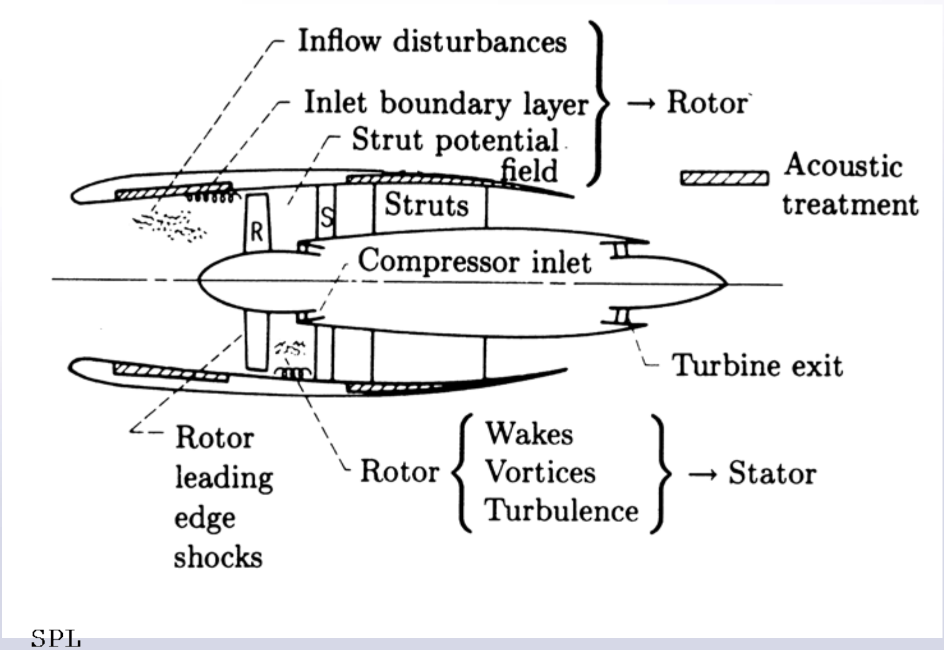
SAMPLE DATABASE

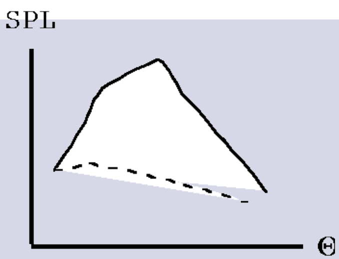
Aircraft Engine Noise

Acoustic Generation



Engine Schematic





OVALS:
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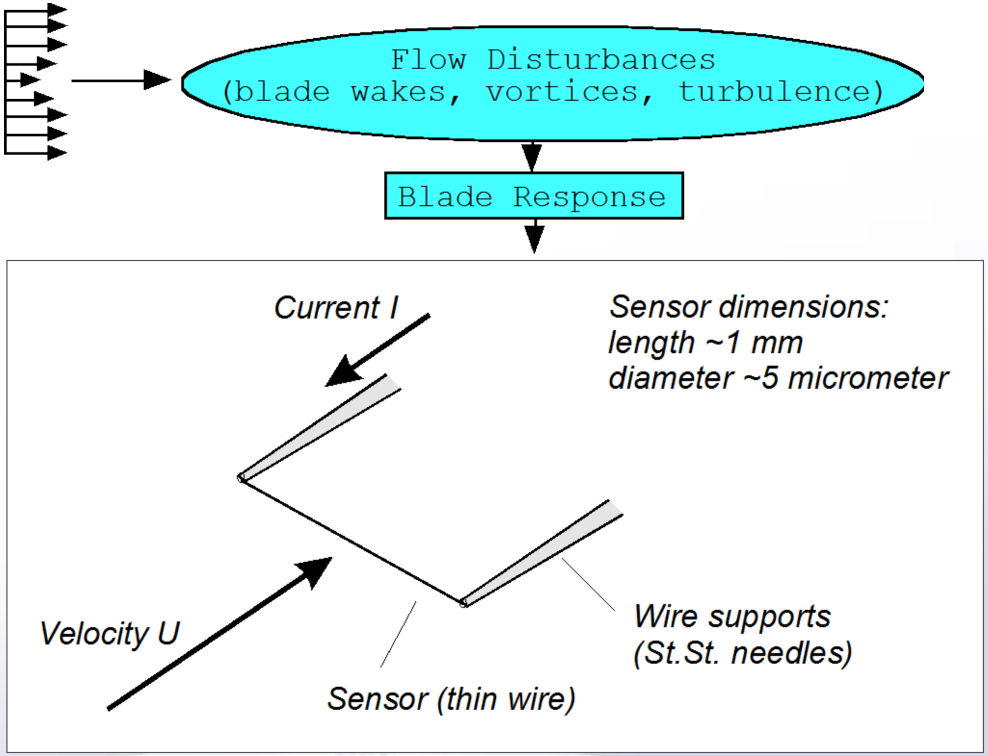
Hotwire (CTA) Measurement



- Hotwire probe used to measure fluctuating velocity behind rotor to obtain wake profile. (CTA)

- Principle of operation:
- Convective cooling of wire by moving fluid.
- To maintain constant temperature (resistance) the current is adjusted.
- Recorded time history of current can be related to velocity by calibration.

Convection Law:
$Q_c = Nu*A*(T_w - T_a)$
Nu = Nussult #
Non-dimensional heat transfer
Collapses non-linear effects

Heating Law:
$Q_h = I^2R$
$Q_h = I^2R0[1-a(T_w - T_0)]$

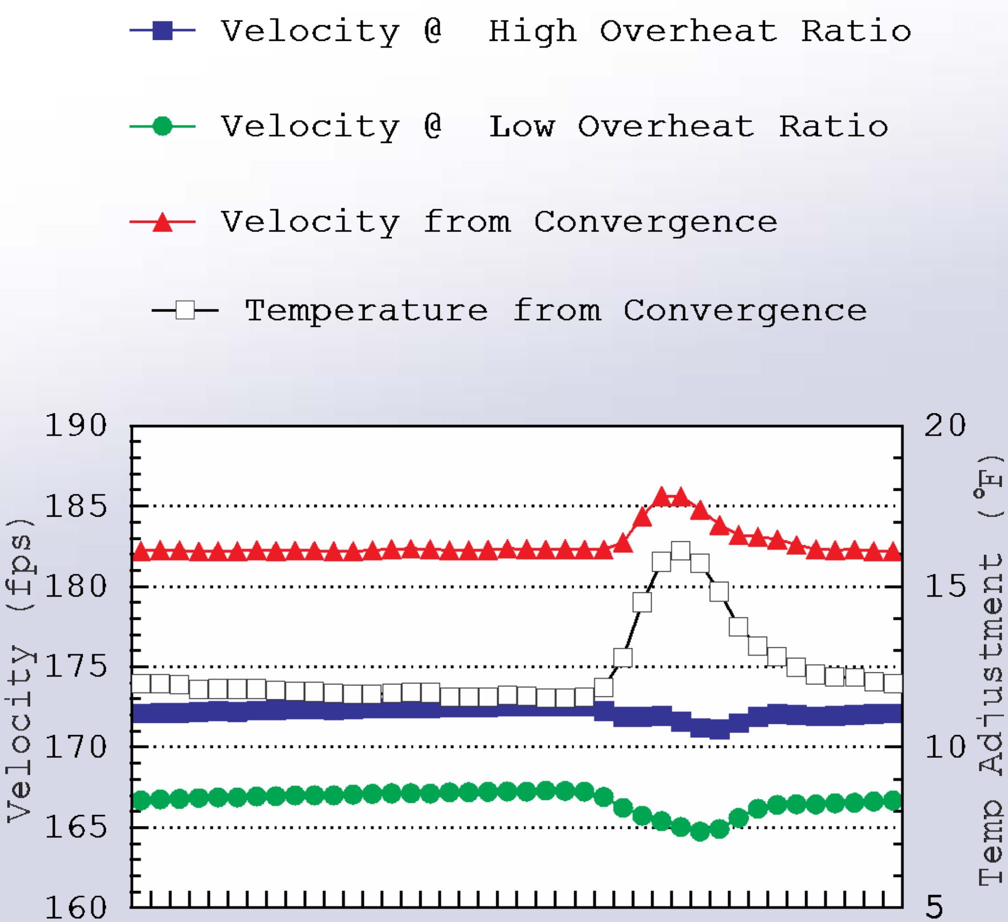
$$\frac{E_w^2}{R_w}(T_w - T_f) = A + BU^n$$

calibration: U -> E
experiment E -> U

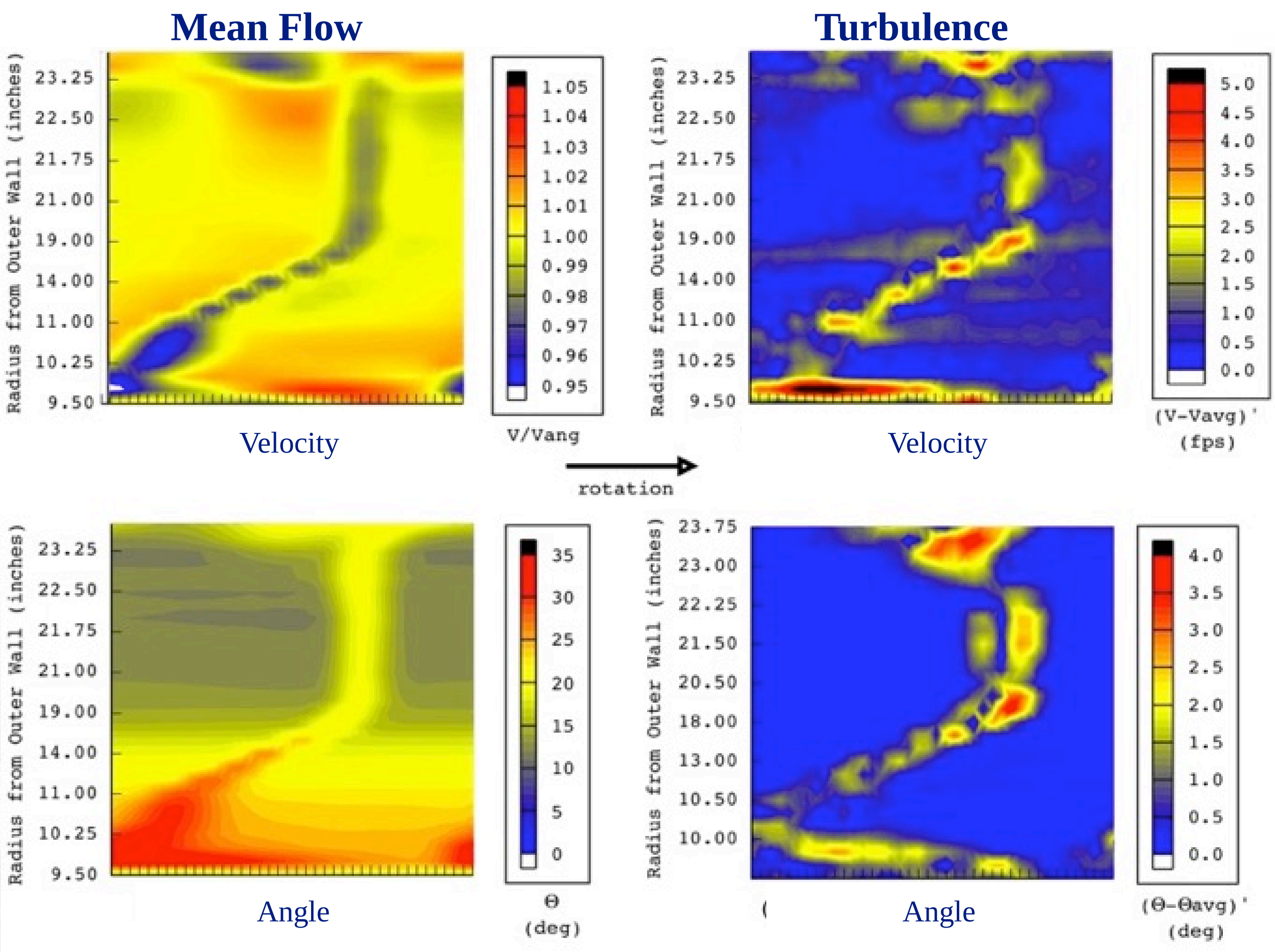
Overheat ratio: T_w/T_f

Rotor Wake Measurement

- Injected air has a temperature rise due to compression.
- This temp difference between the wake and the mean flow causes measurement air.
- To correct this the two-overheat method was implemented.
- Essentially two unknowns, (V_i, T_i) and two equations



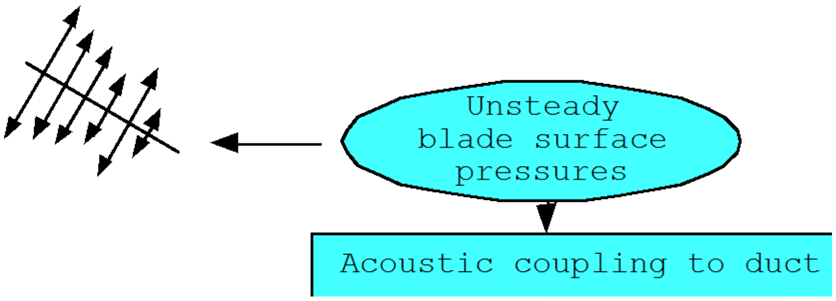
Flow Measurements

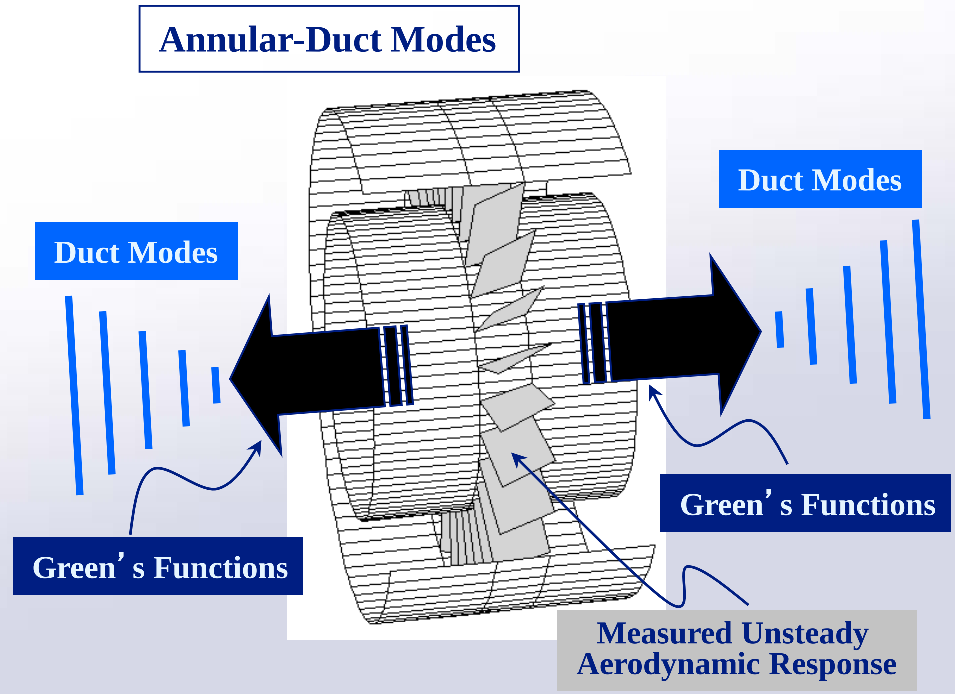


CONTOURS BEHIND ROTOR

Two-Component Hot-film (ensemble averaged over one passage)

Stator Vane Surface Pressures

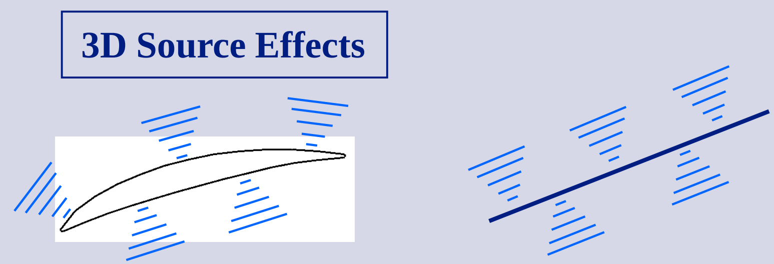




- Acoustic analogy formulation based on *uniform-flow*, *annular-duct* Green's functions is used to represent the duct acoustics.

- Unsteady surface pressure *measurements* are used as aerodynamic input to the analytical model.

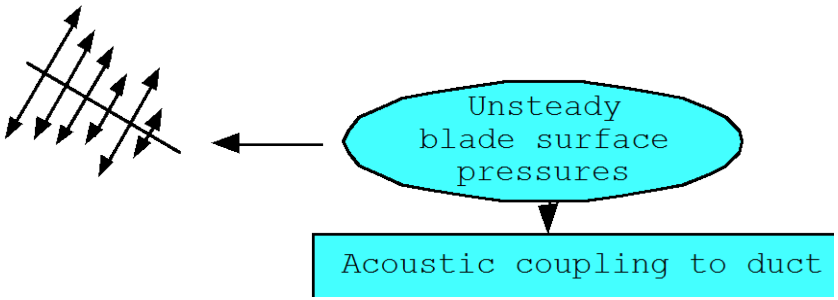
$$p'(\vec{x}) = \iint Q(\vec{x}|\vec{x}_s;\omega) f(\vec{x}_s;\omega) d\vec{x}_s$$



Acoustic Radiation form a 3D Airfoil Section

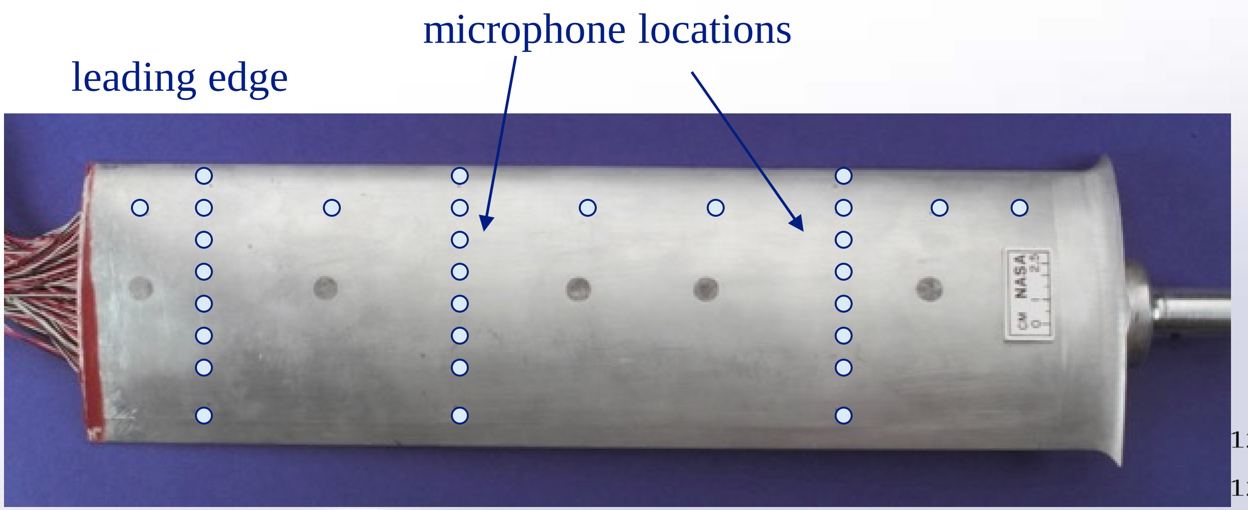
Acoustic Radiation in Classical Flat-Plate Approximation

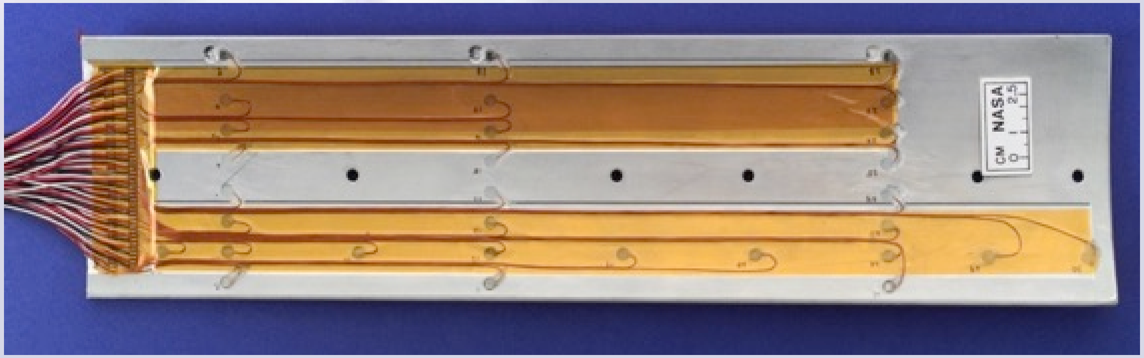
Stator Vane Surface Pressures

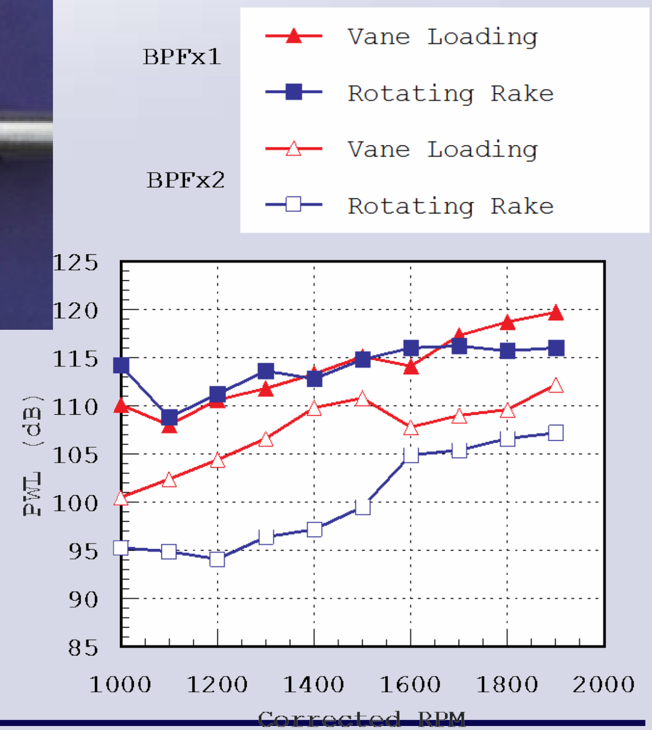


•Stator Vane surface pressures an excellent predictor of noise.

$$p_l = \frac{S_v}{10^{-12}\rho_0 a_0}\left\{\frac{1}{3}\left[\sum^{41\%,74\%,94\%}\left(\Delta\overline{P}_{rms}\right)\right]^2\right\}$$

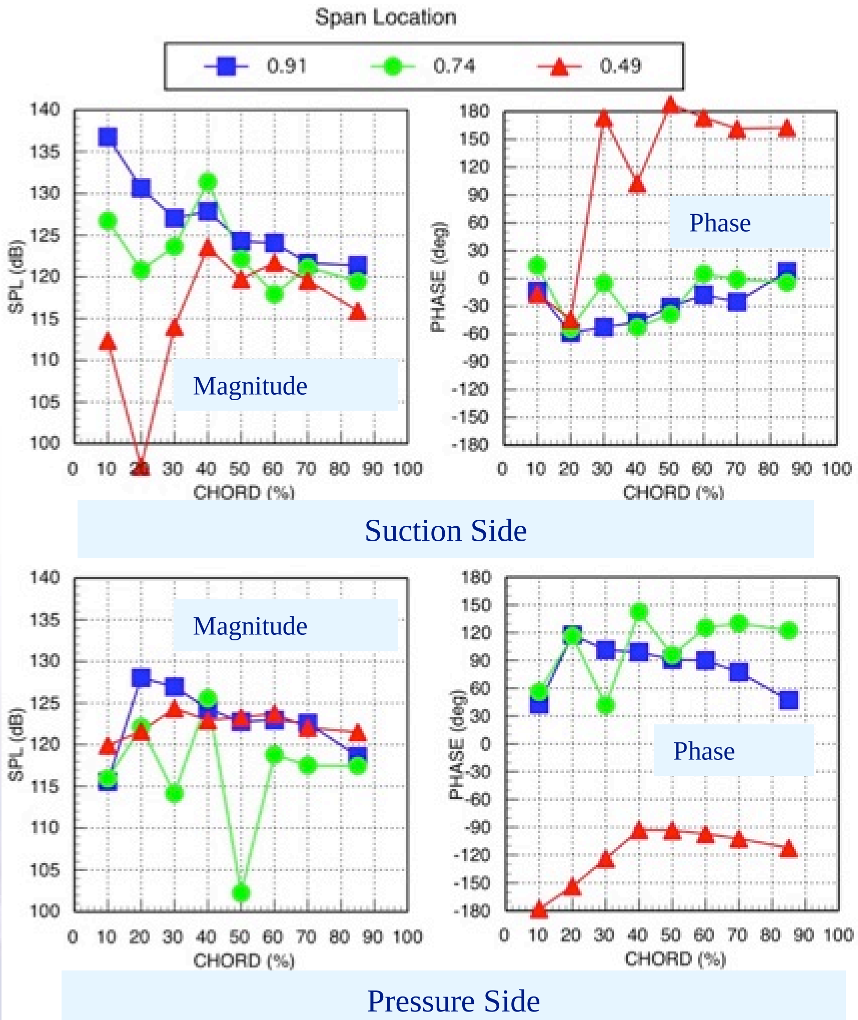




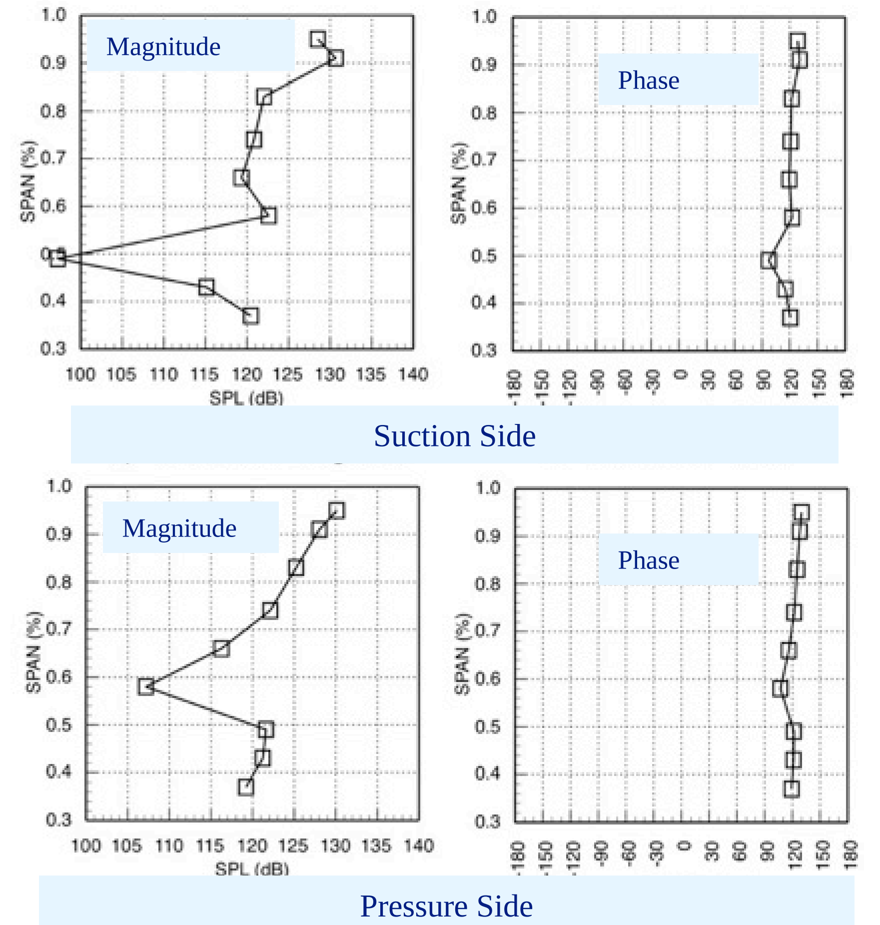


Stator Vane Un-Steady Surface Pressures

3-CHORDS



SPAN



BPF Tonal Unsteady Vane Pressures

Acoustic Duct Mode Patterns

Acoustic coupling to duct

solution to separated wave equation:

$$P(\theta,r,x,t) = p_{mnf} * E_{mn}(k_{mn}r)e^{i(2\pi ft+m\theta\pm\gamma x)}$$

2-Dimensions:

circumferential direction:

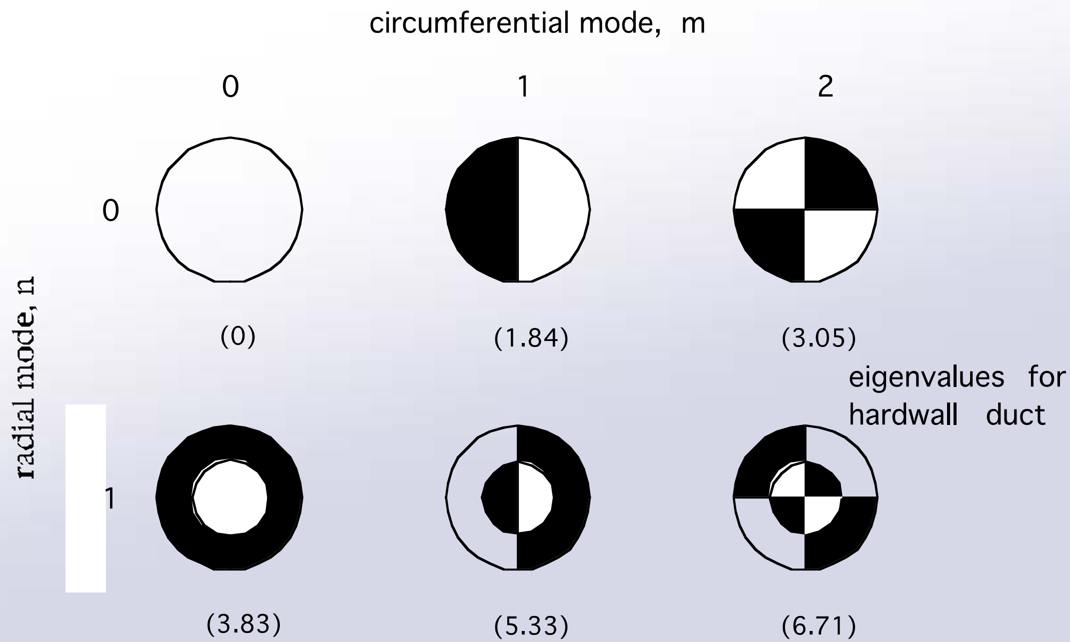
$$P(\theta) = P(\theta+2\pi); \quad \sin(m\theta)$$

m is defined as the number of cycles
-circumferential mode, m order

radial direction:

$$E_{mn}(k_{mn}r) = C_{mn}[J_m(k_{mn}r) + Q_{mn}Y_m(k_{mn}r)]$$

n is defined as the number of zero crossings
-radial mode, n order

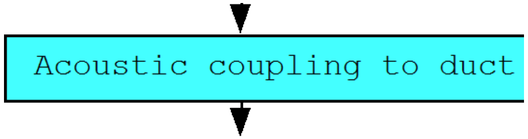


eigenvalue problem based
on boundary conditions:

$$0 = [J'_m(k_{mn}r) + Q_{mn}Y'_m(k_{mn}r)]; \quad r = r_t, r_h$$

J & Y are Bessel functions of the 1st kind
k & Q are “eigenvalues”

Rotor-Stator Interaction

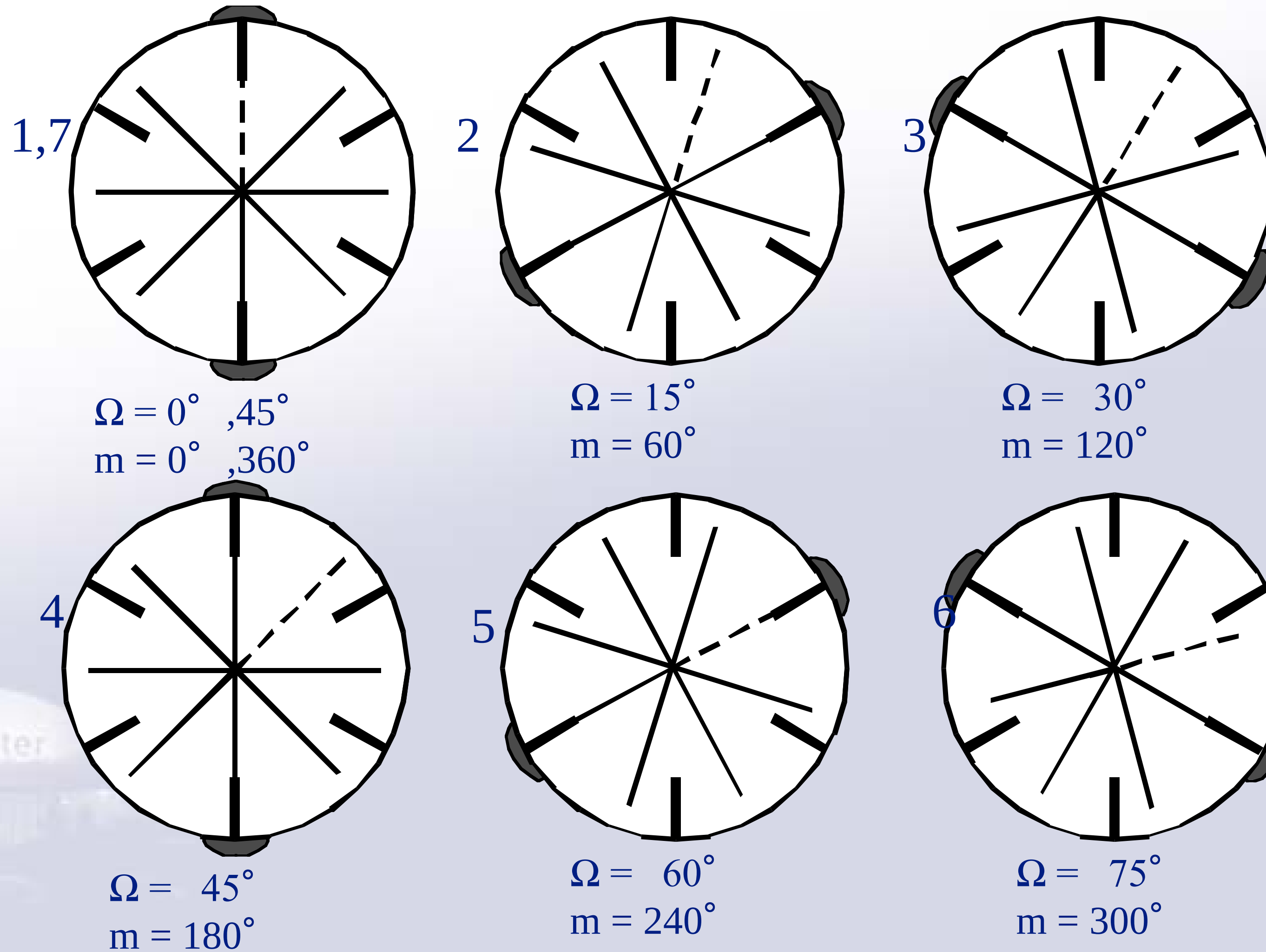


rotor blades,B = 8
stator vanes,V = 6

This interaction leads to a 2-lobe pattern which completes a cycle in 1/4 rotor

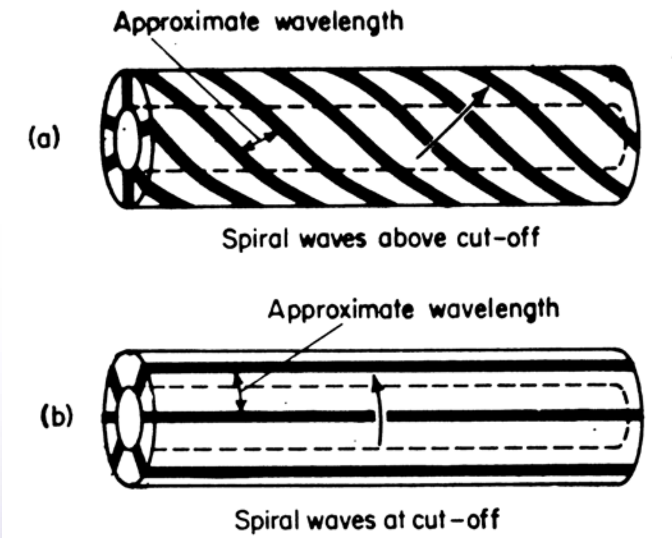
m = nB - kV
(n harmonic, k= any integer)

$m^*\Omega_{mode} = B^*\Omega_{rotor}$
$\Omega_{mode} = (B/m)^*\ \Omega_{rotor}$



Duct Propagation

Duct propagation
blade row transmission



3-dimensional propagation

axial wavelength:

$$\gamma_{mn}(x) = \sqrt{(2\pi f r_t / c)^2 - k_{mn}^2}$$

$$i) \quad 2\pi f r_t / c > k_{mn}; \quad \gamma \ real, cyclical \ propagation$$

$$ii) \quad 2\pi f r_t / c = k_{mn}; \quad cut-off \ frequency$$

$$iii) \quad 2\pi f r_t / c <; k_{mn}; \quad \gamma \ imag, \mathrm{exp}onential \ decay$$

define the cut-off ratio from (ii)

$$\zeta = f / f_{co}; \quad \begin{matrix} >1 \ propagates \\ <1 \ decays \end{matrix}$$

physically, 3D waves are helix--propagation angle
highly cut-on modes approximate plane wave (a=0°)
cut-on modes axial wavelength is longer than free space
(shorter wavenumber)
cut-off modes have ‘infinite’ axial wavelength
(zero wavenumber -- decay)

Rotating Rake Concepts

Duct exit acoustic mode content

Continuously rotating, radially distributed from tip to hub array of pressure transducers installed at inlet/exhaust duct acoustic release point.

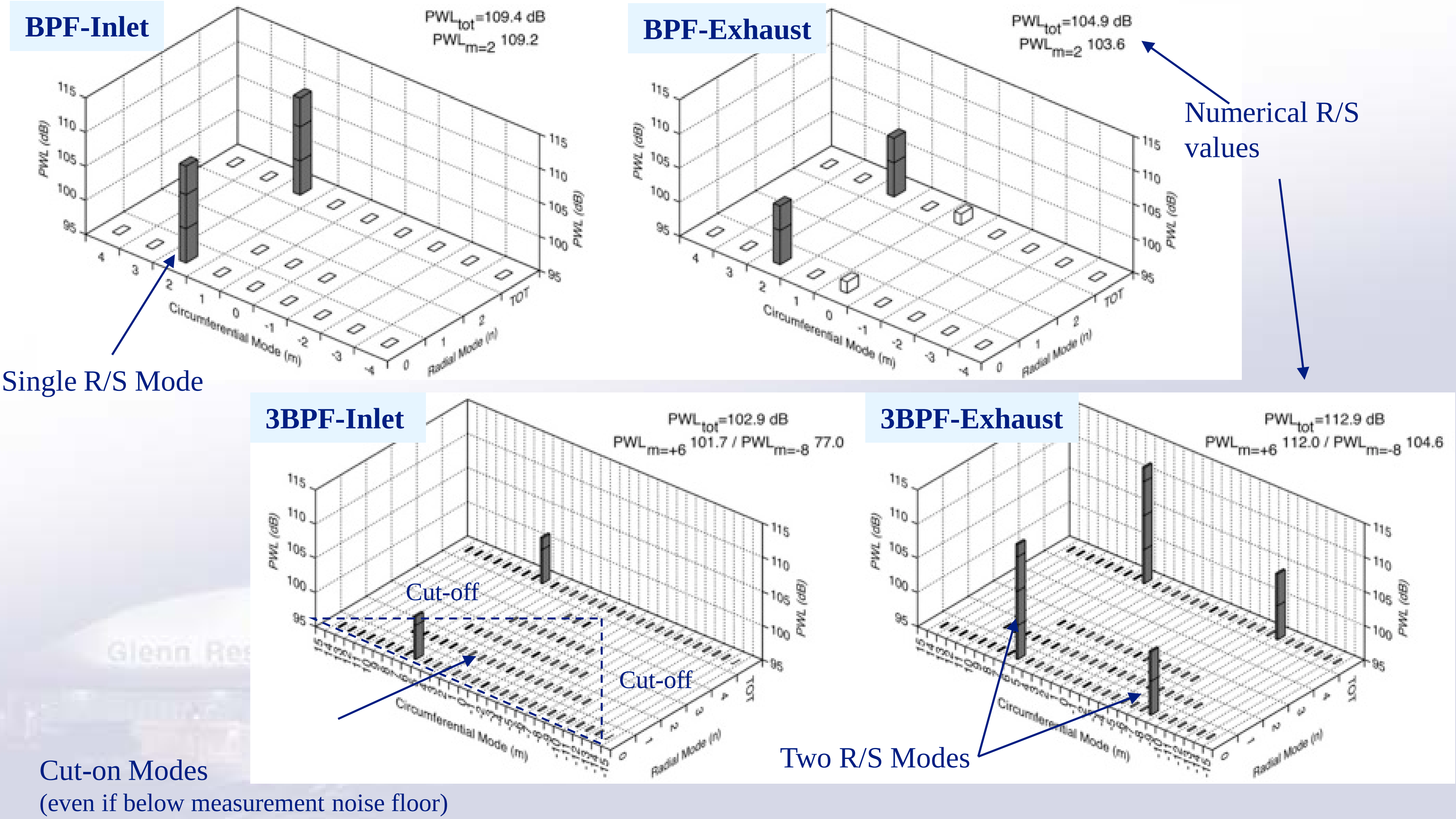
- Rake electronically very accurately synchronized to fan shaft
  - 1/100th fan speed, i.e. 18 rpm
  - +/-0.2° absolute error
- Signals brought across rotating boundary via telemetry
  - 7 inlet, 6 exhaust transducers

KEY CONCEPT: Each m-order rotates at a different spin rate.

- The rotating rake imparts a unique Doppler shift depending on spin rate, hence m-order.
- Radial modes in a given m-order complex curve fit using least-squares fit to the derived duct E-functions.

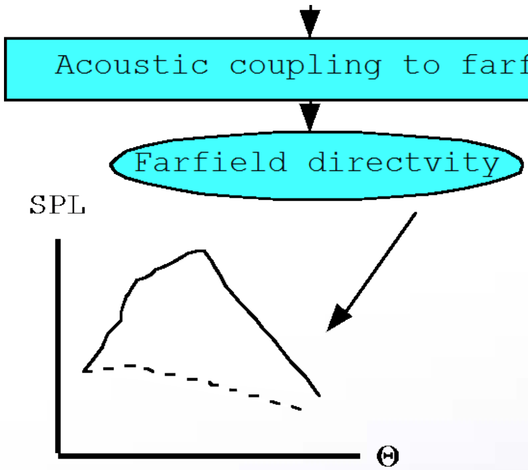
A complete circumferential and radial modal magnitude & phase map is obtained for the 1st three harmonics

Duct Modes / Rotating Rake

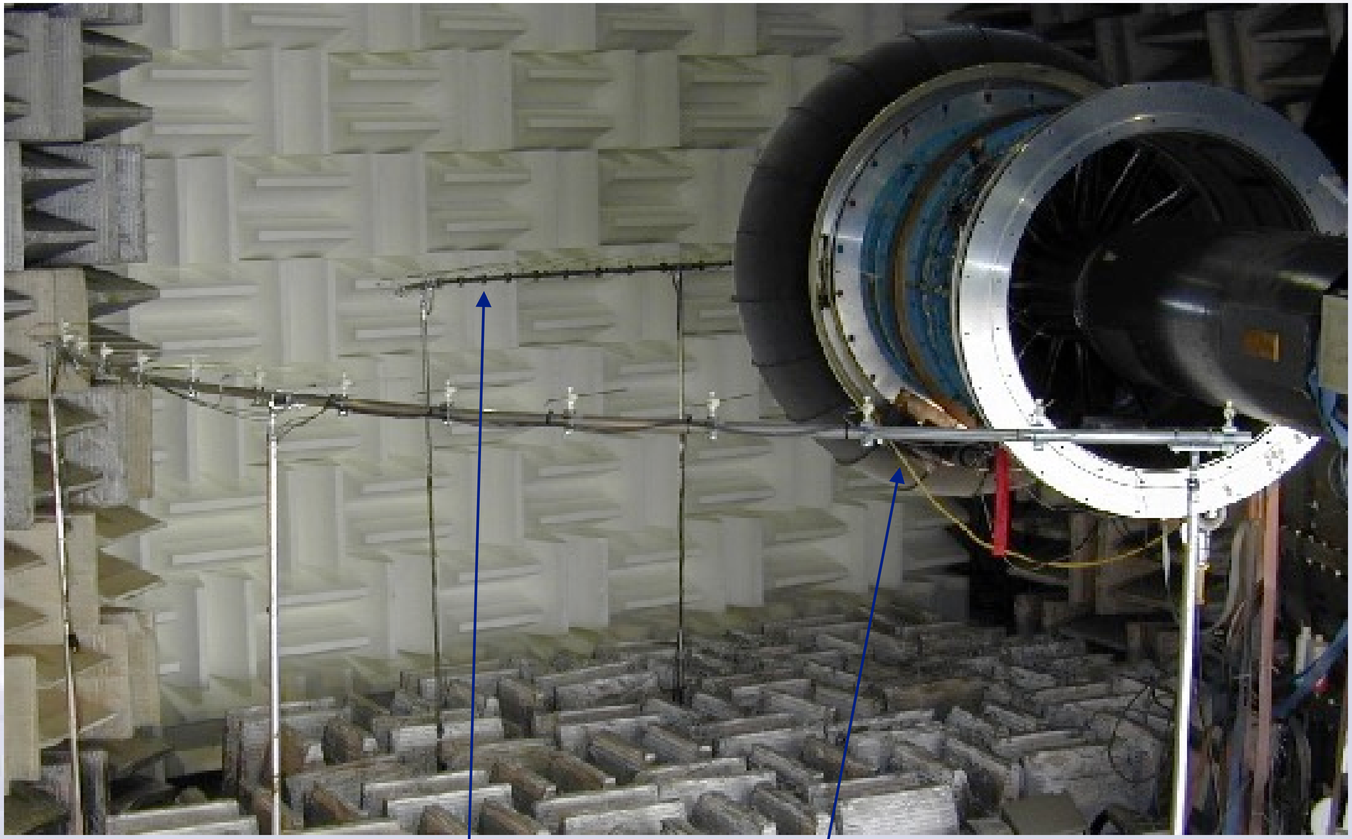


Modal Plots with 14 Stator Vanes at 1-Chord; 1800 RPMc

Farfield Measurements



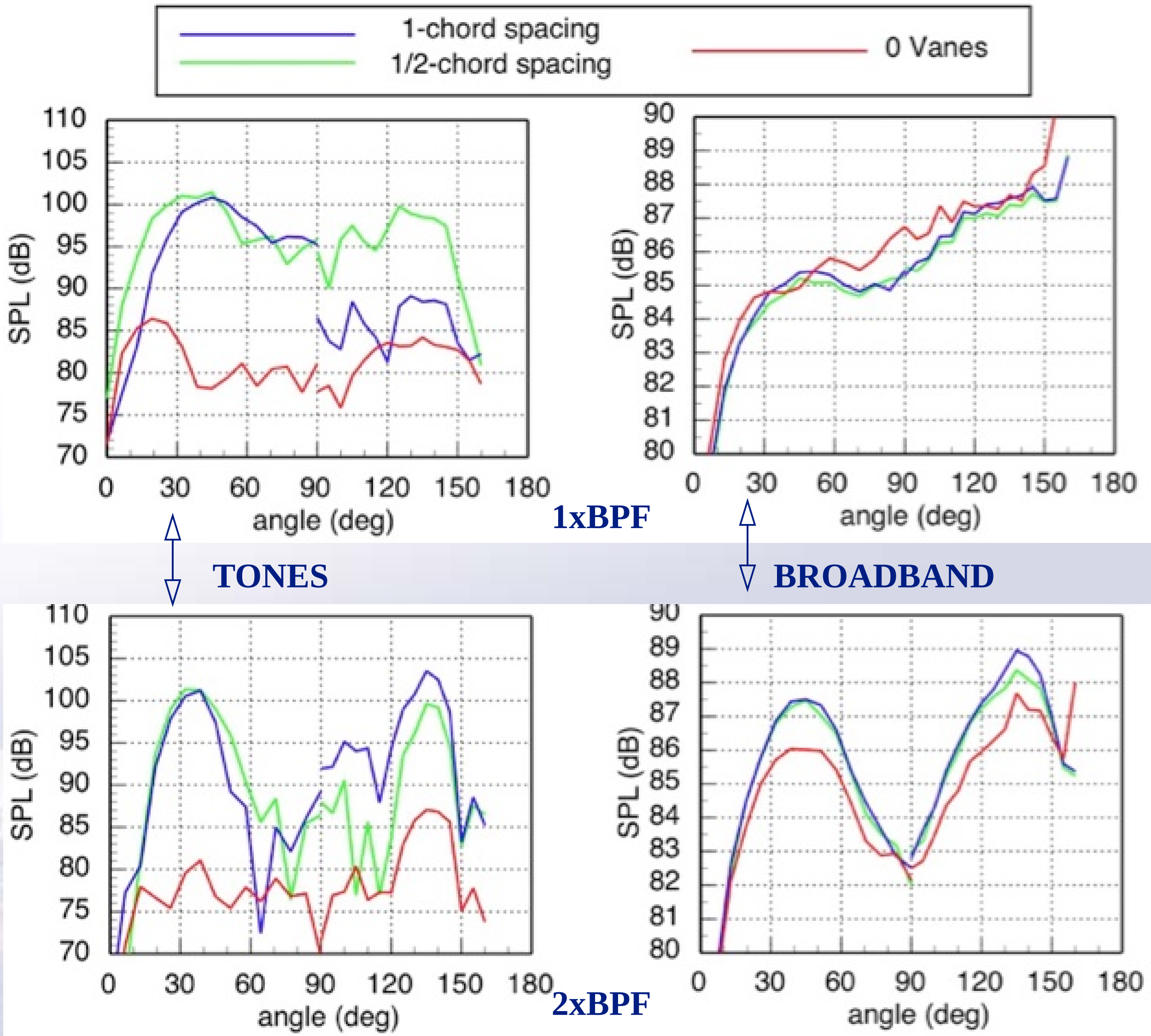
- Acoustic pressure in farfield is the ultimate metric.
- Integrate over volume to get total power (PWL).
- FAA requires detailed weighting for EPNL.



farfield microphones
(15 fwd @ 8' / 30 aft @ 12')

Farfield Acoustics

Large 20 dB tonal penetration due to stators



1-2 dB increase in broadband due to stators

Farfield Directivities with 14 Vanes Installed Compared to Rotor Alone

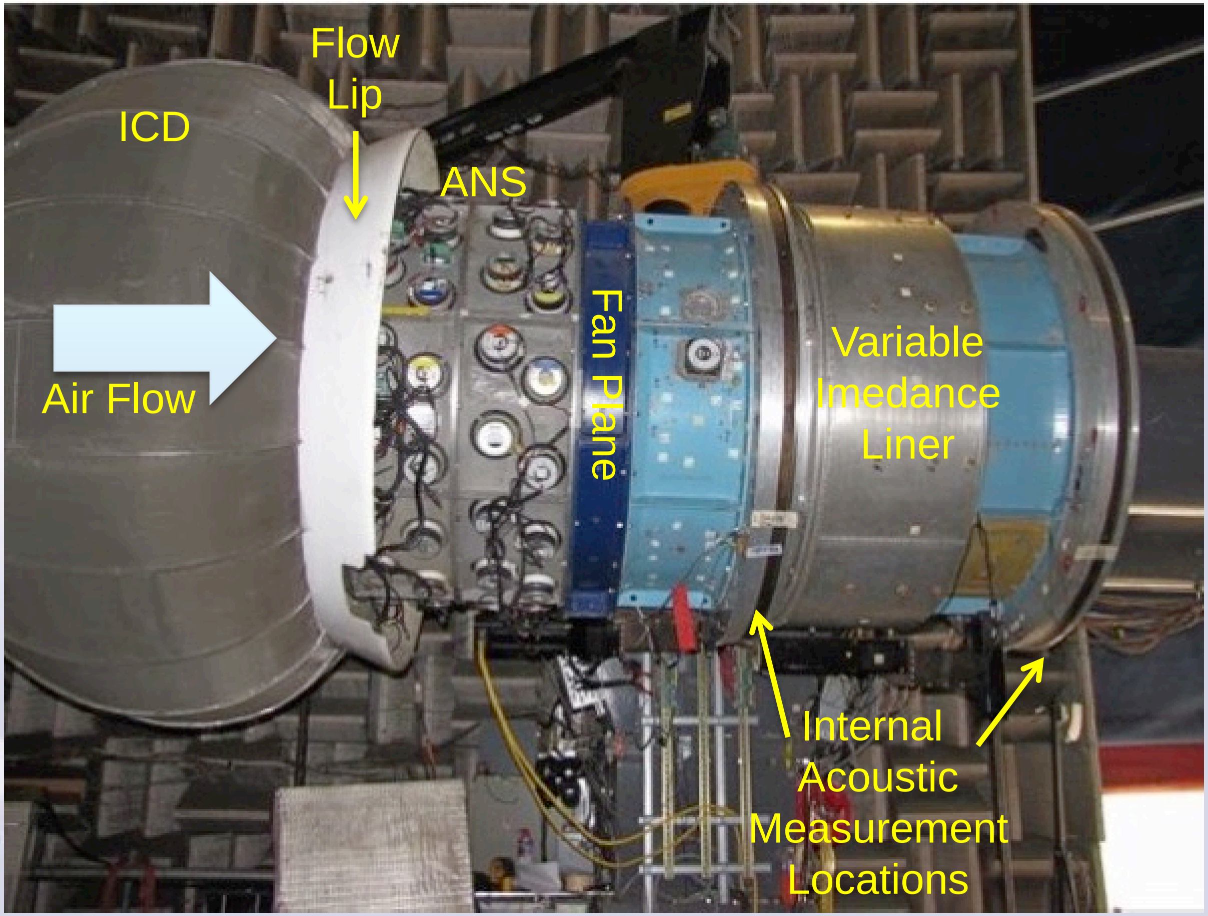
UNIQUE CONFIGURATIONS

Horizontal Orientation

Selected configurations were tested on the stanchion with the fan generating the acoustic signature (standard mode of operation).

This provided for the inclusion of flow, and non-uniform geometry effects.

Also, measurements of far-field acoustic directivity were acquired for confirmation of community impact.

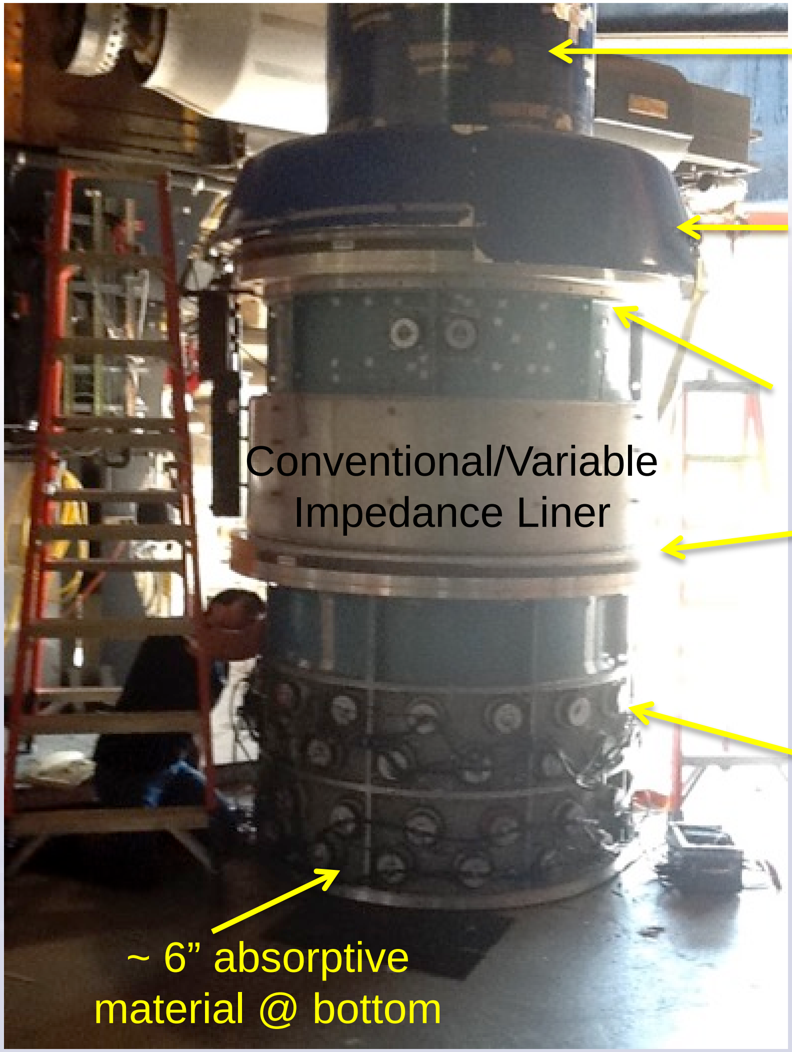


Vertical Orientation

A significant portion of the data was acquired with the rig built-up in a vertical orientation.

(off of the stanchion; no rotor/stator – no flow, very clean internal lines).

This unique configuration allowed for very precise analytical solutions to evaluate the efficacy of the liner(s) and the accuracy of CDUCT-LaRC.



Configurable Fan Artificial Noise Source(s)

Initially 32 channels (upgrade to 64).

4 rows of 16 drivers each

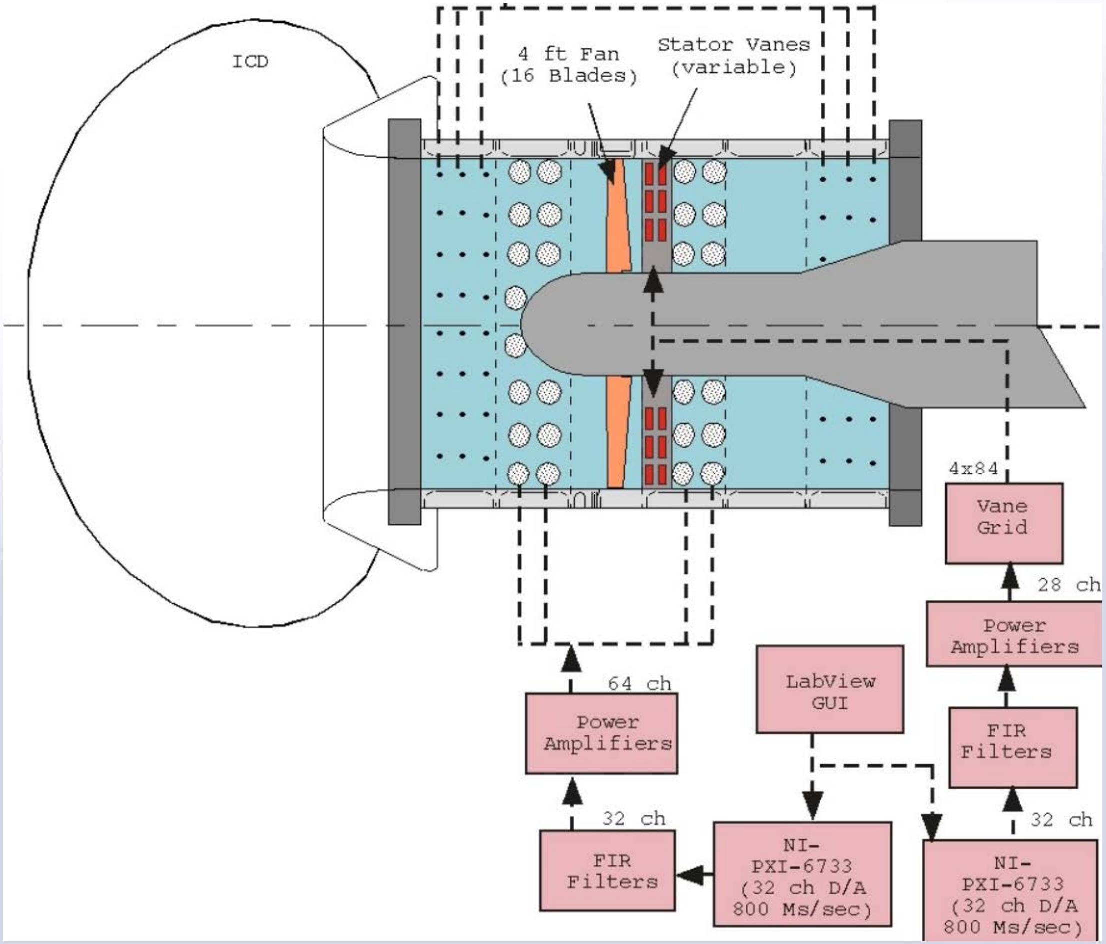
Generate noise source in S/W. Each channel independent.

Labview VI's or 2x32 channels of FIR filters to 'shape' output.

Use of phase delays to simulate modal vs random sources.

Use of time delays to simulate rotating vs stationary sources.

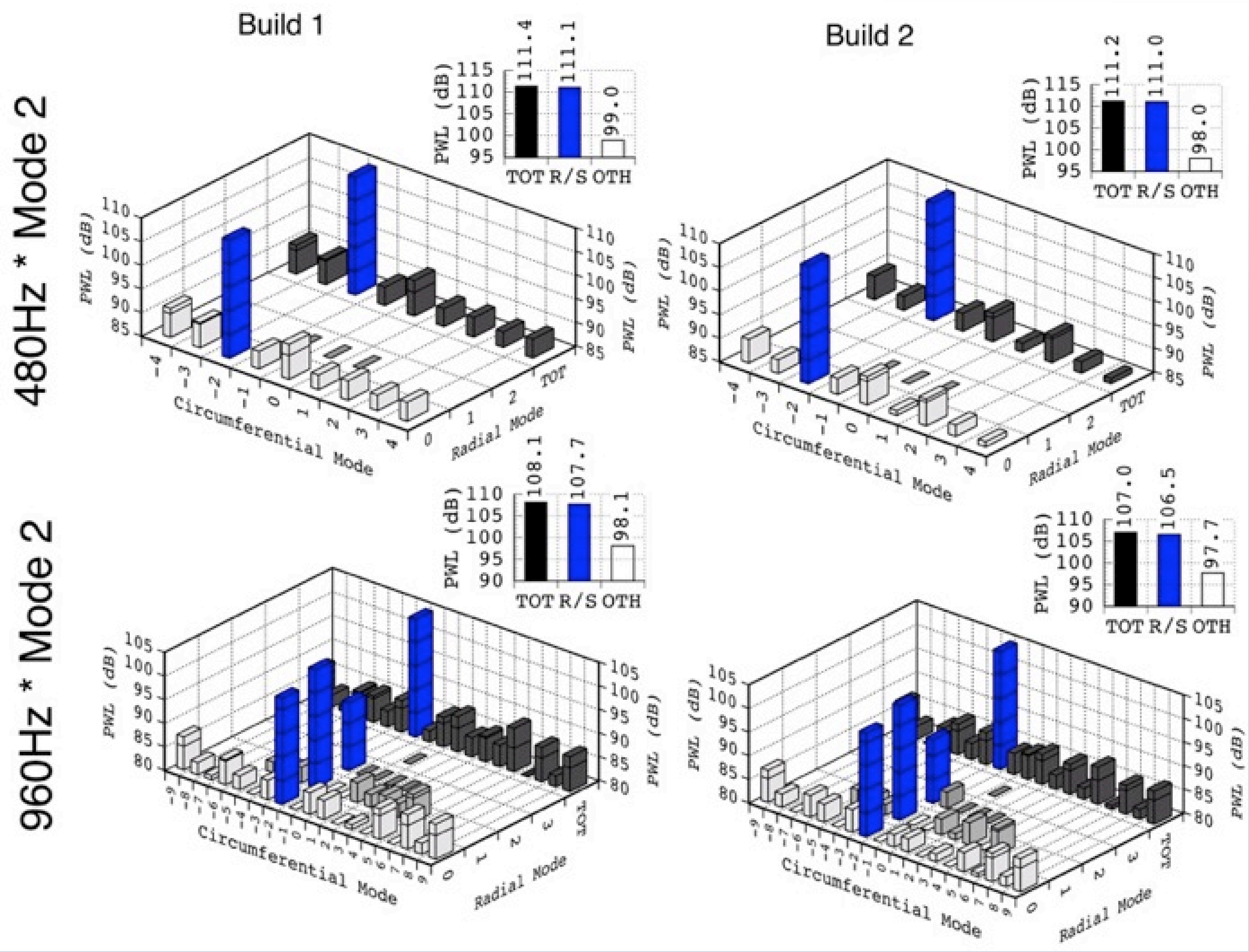
General Range:
250 Hz < freq < 1500 Hz
$|m| < 6$; n<4



CFANS – Performance

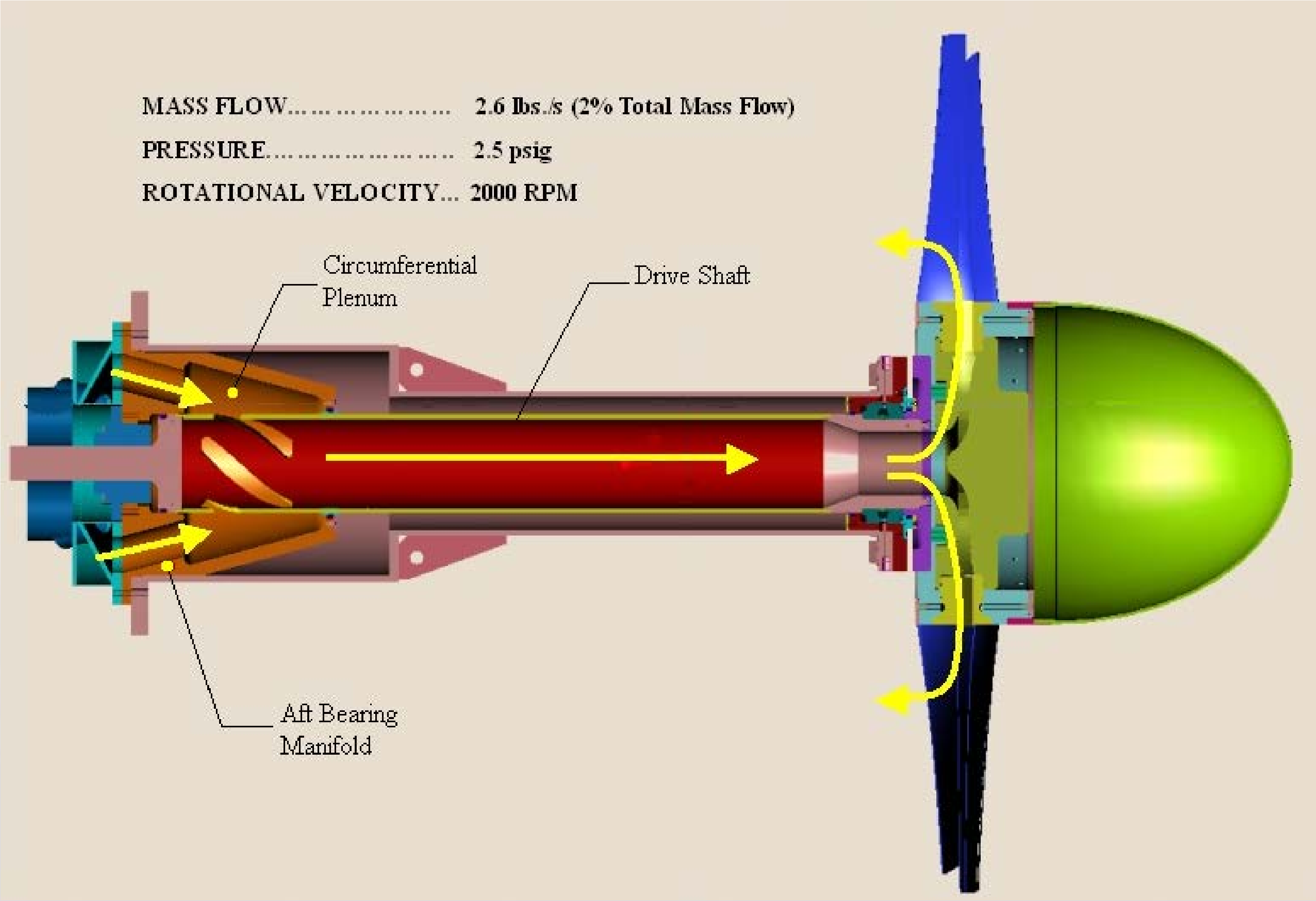
Typical Results – Generated in Exhaust/Measured in Inlet

+ 20 dB target mode S/N + 10 dB total PWL S/N ~ 1 dB repeatability

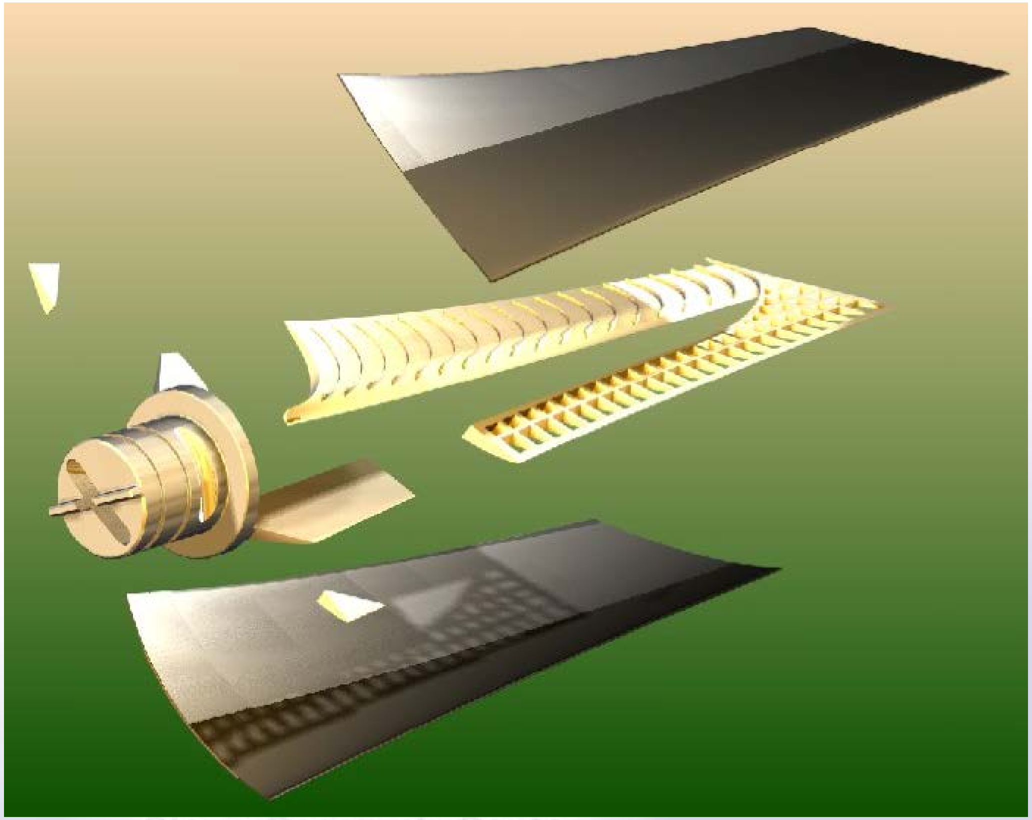


NOISE REDUCTION CONCEPTS EVALUATED

Trailing Edge Rotor Blowing (TERB)

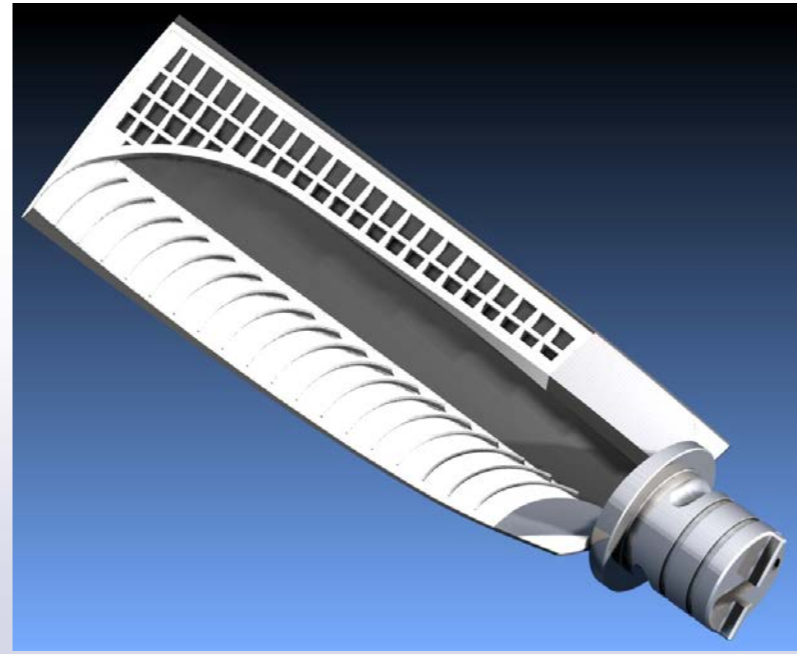


TERB - Composite Hollow Blades



Composite rotor blades with hollow plenum assembly created by cast mold that locates and holds components.

- flow boundaries from a single laser-sintered piece
- blade skin made of graphite/epoxy laminates

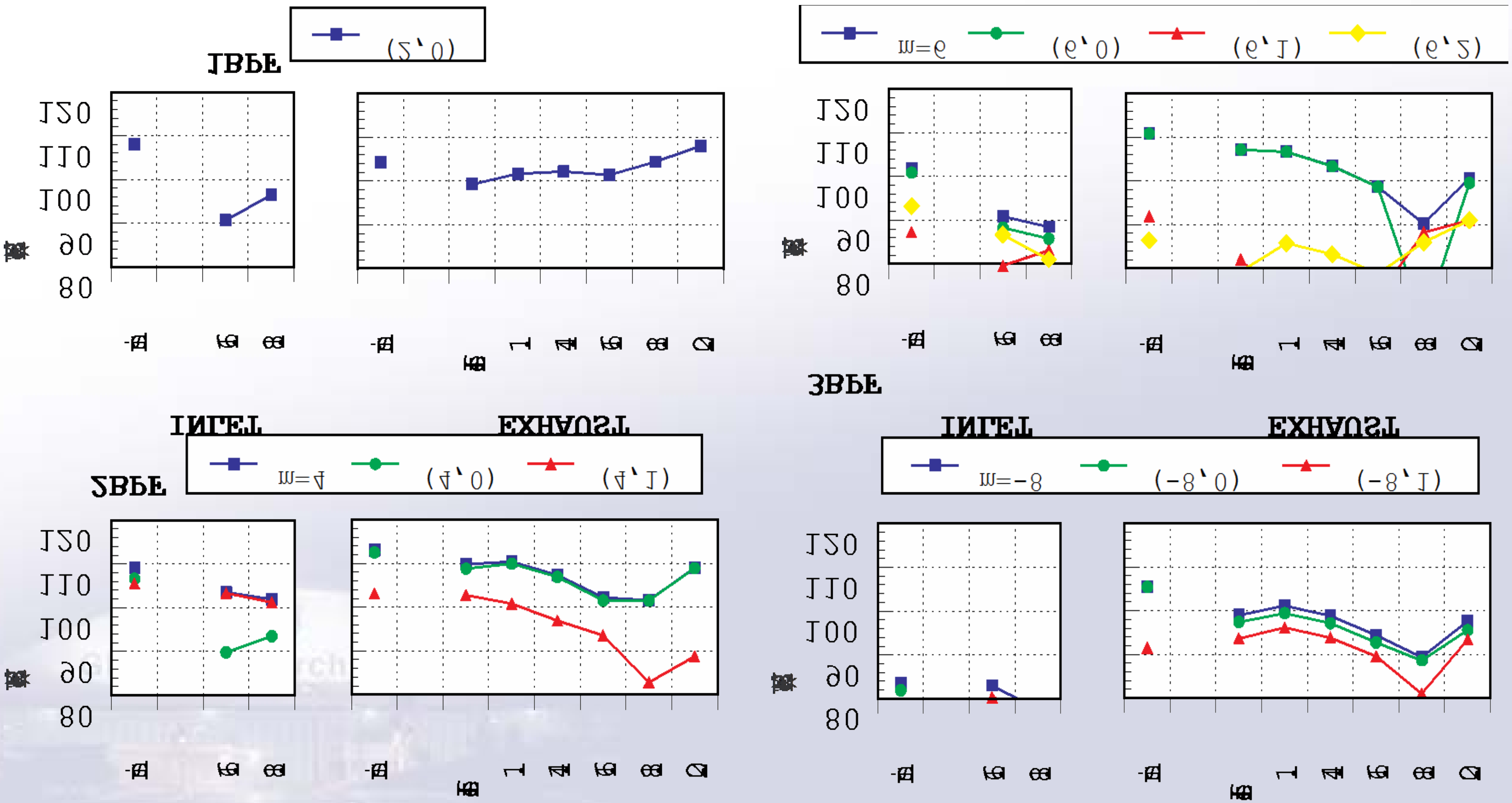


Internal flow channel shapes were designed using 3-D viscous CFD code, RVC3D in an iterative process.

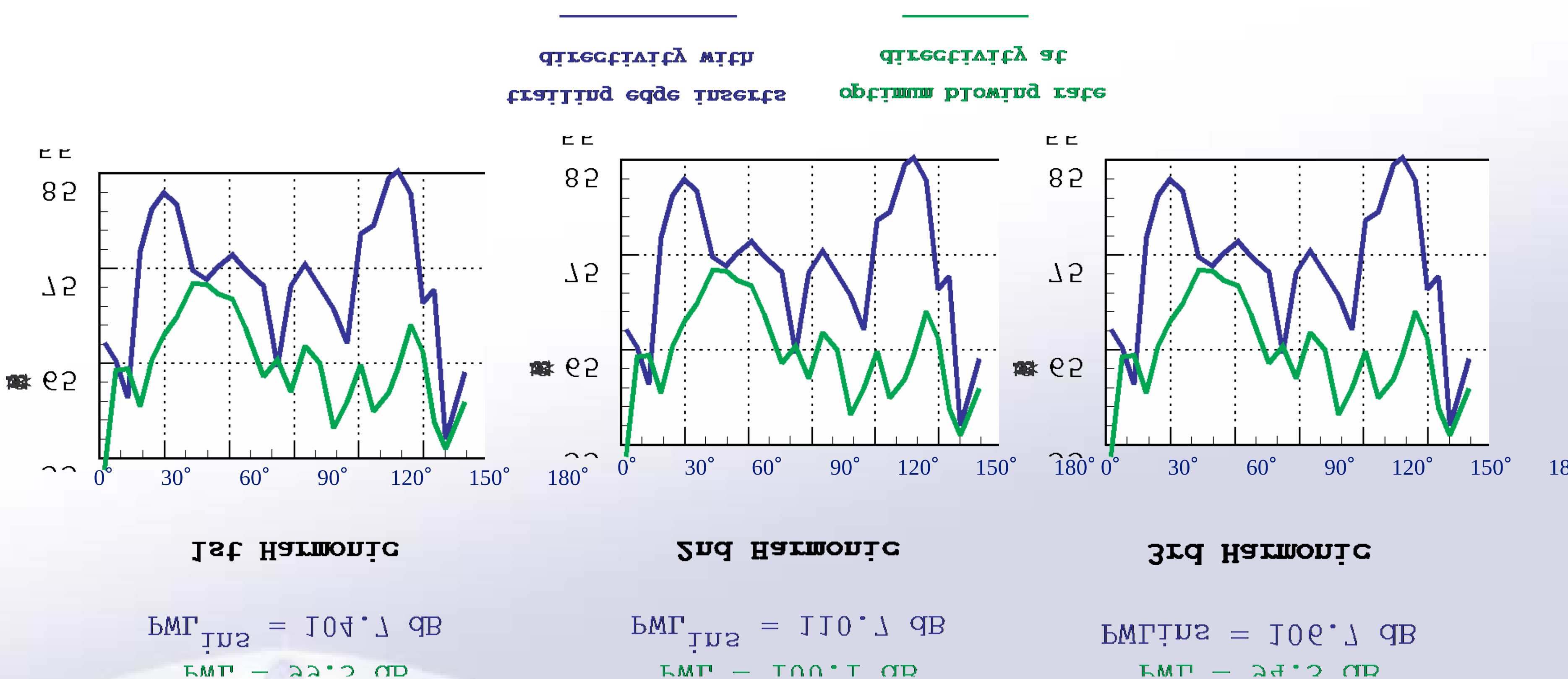
Bench tested for flow and structure.

TERB - R/S Interaction Modes vs Blowing Rates

Minimum generally occurs at ~1.8% except at BPF exhaust



TERB - Farfield Directivity

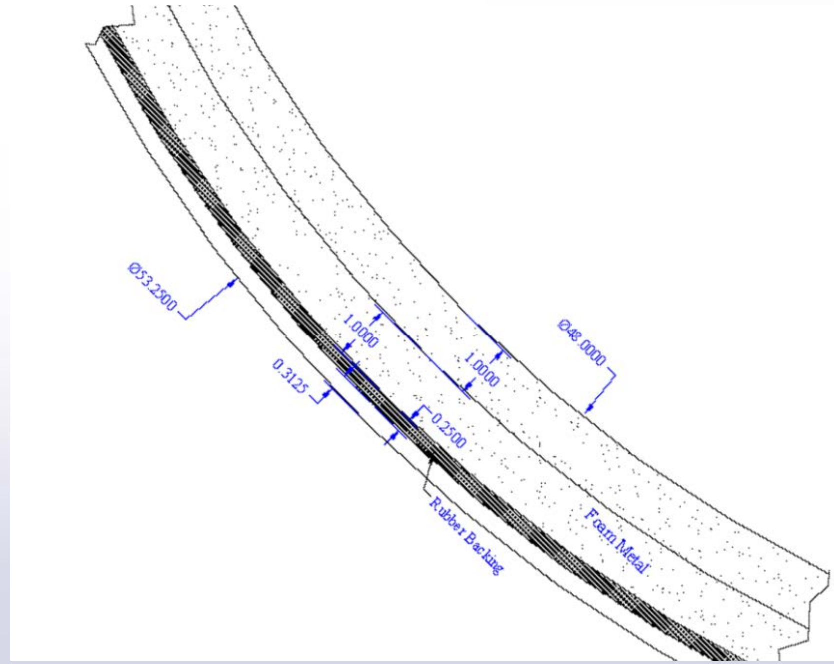


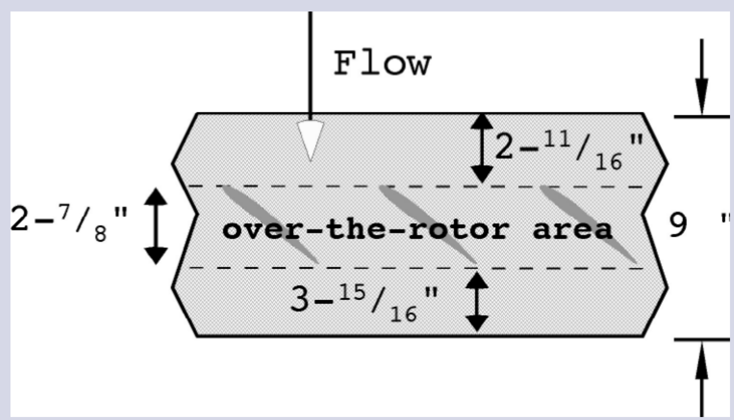
Farfield reductions correlate very well to In-Duct reductions

Optimum blowing rate at 1.6% (slightly lower than in duct)

Reduction at other RPM consistent

Over-the-Rotor Foam Metal Liner (OTR/FML)





OTR/FML – Configurations Tested

- Liner Configurations tested:

L = 9”, d=2”; 80ppi @ 6-8%

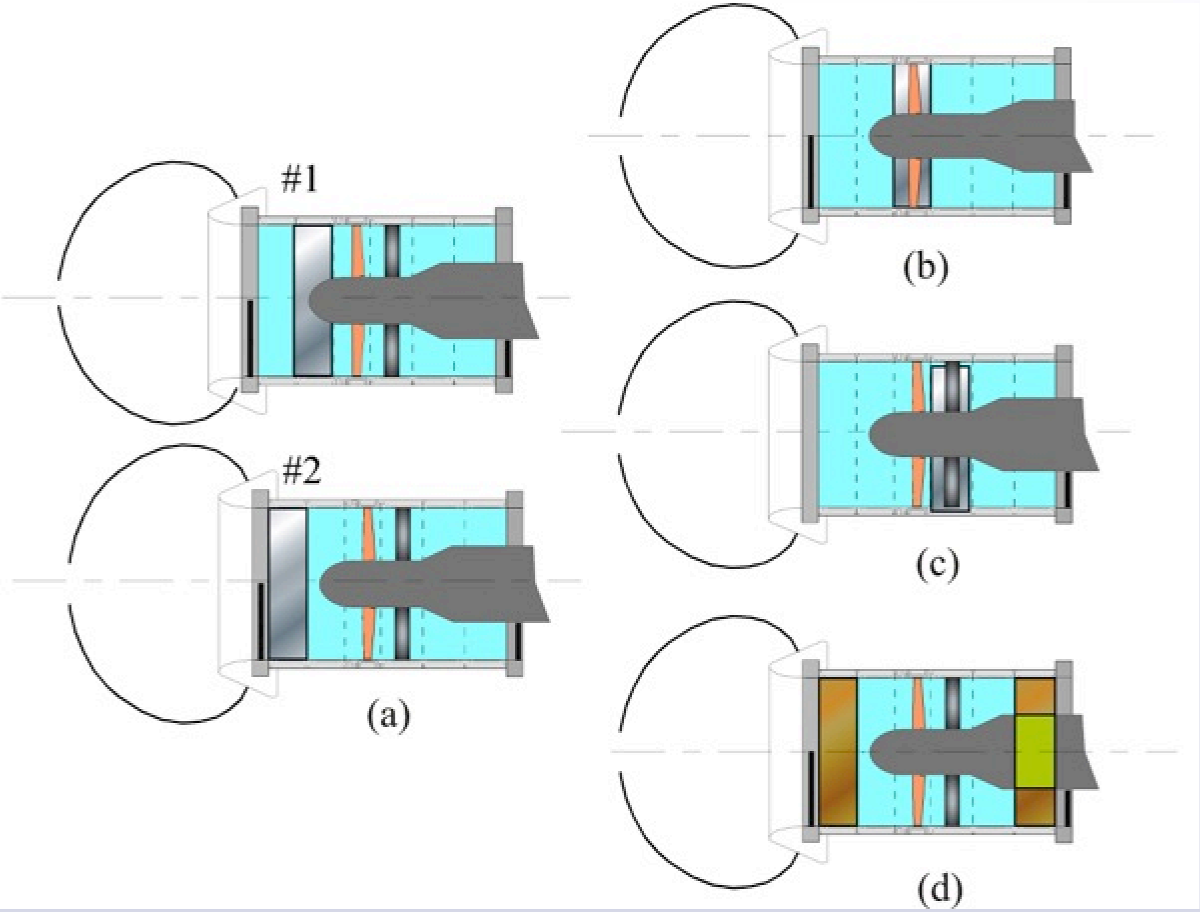
(a) FML in 2 inlet locations

(b) FML Over-the-Rotor
- 1” & 2” depth
- 1/32nd & 3/32nd tip gap

(c) FML Over-the-Stator

(d) SDOF liner in inlet & exhaust ducts

- Unique hardwall baseline created by taping over liner(s) in each configuration.



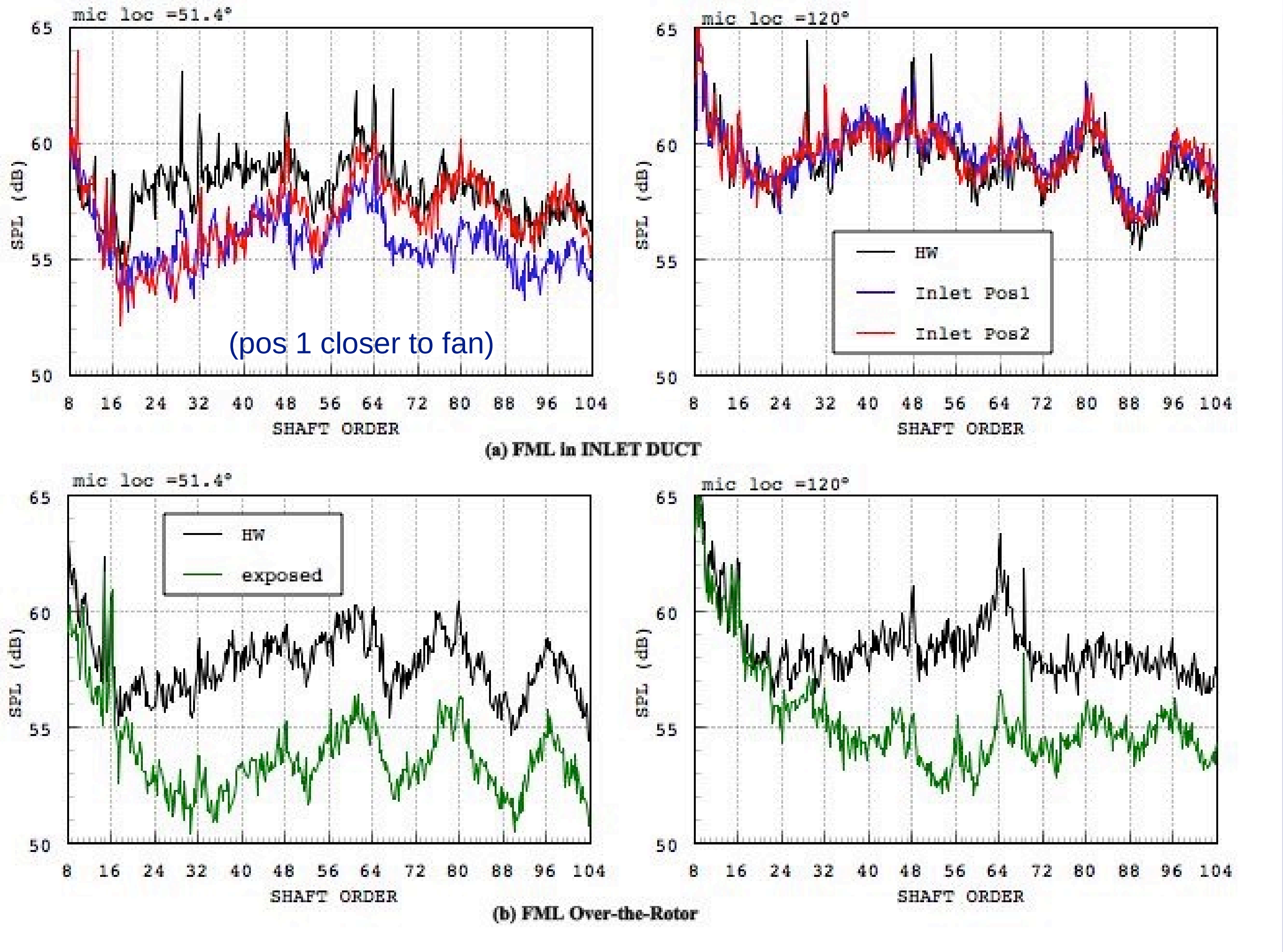
OTR/FML – Spectral Characteristics

INLET POSITION:

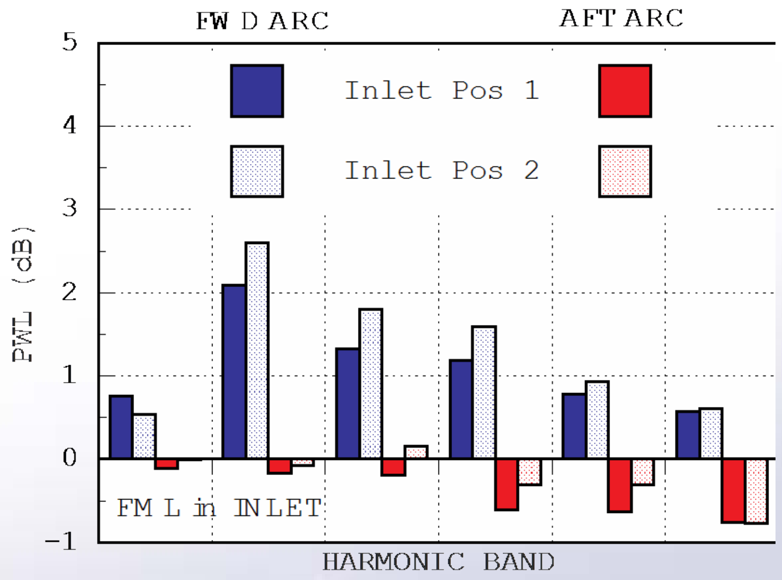
~3 dB attenuation from 1 - $3^1/_2$ BPF

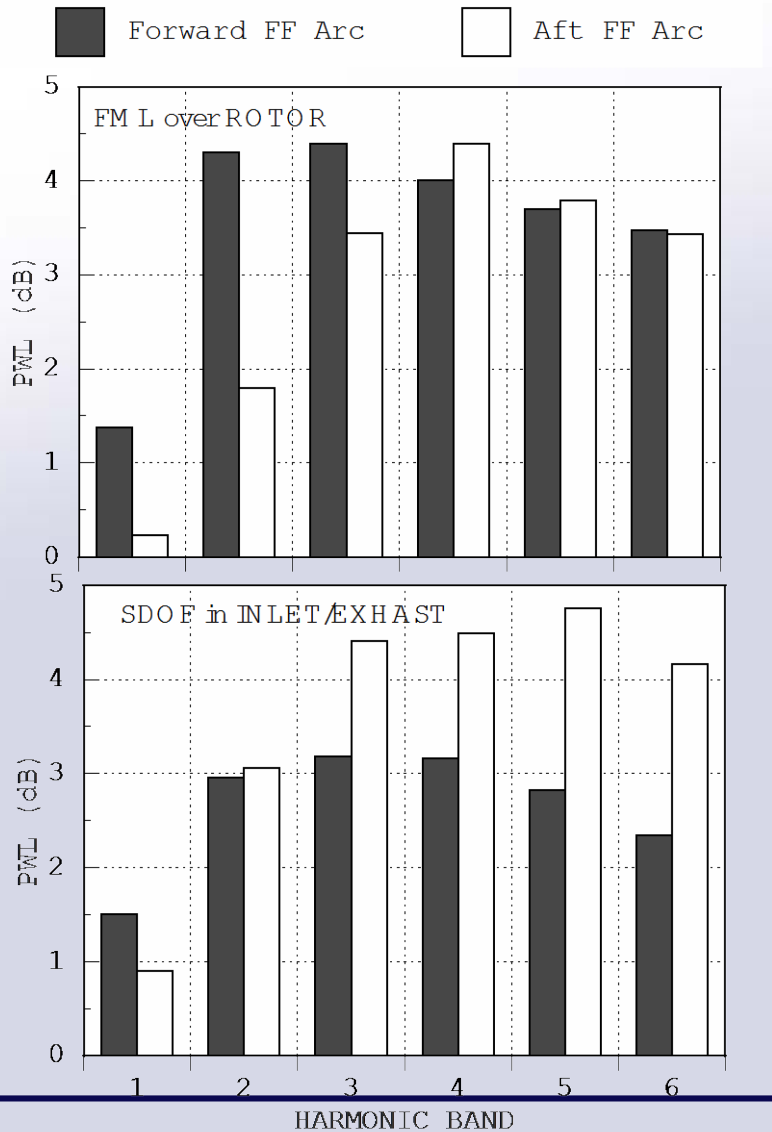
OTR POSITION:

~5 dB attenuation from BPF and above



OTR/FML vs SDOF FF-BB PWL Reductions





Axial Extent of

- •Single Degree of Freedom Liner ~3 x 18”
- •Foam Metal Liner ~ 9”

Liner Studies

Collaborating with Mike Jones (Langley) & friends

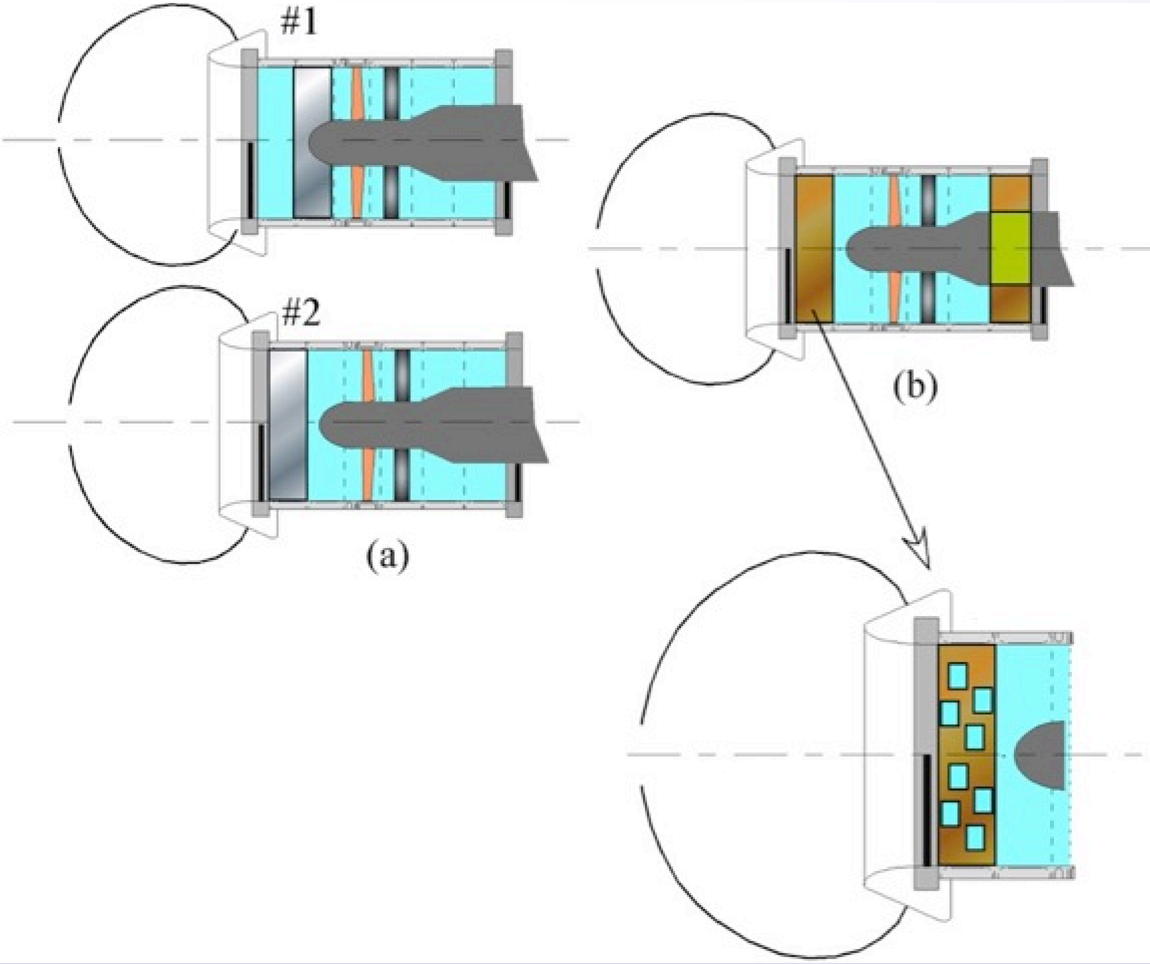
(1) Validation of liner research TRL path
(2) Checkerboard Liner
(3) Extended Reaction Liner

Extended Rotating Rake to measure modes over treatment. Artificial sources for larger modal database.

VPI LIner: Two linear single-degree-of-freedom (SDOF) liners with a screen mesh on a 34 percent POA perforate were used in these experiments. The normalized design resistance for the two liners is 1.0 ρc and 1.7 ρc. The liner core depth is 1.0 and 0.85 in.; resonance frequencies are 2872 and 3221 Hz, respectively.

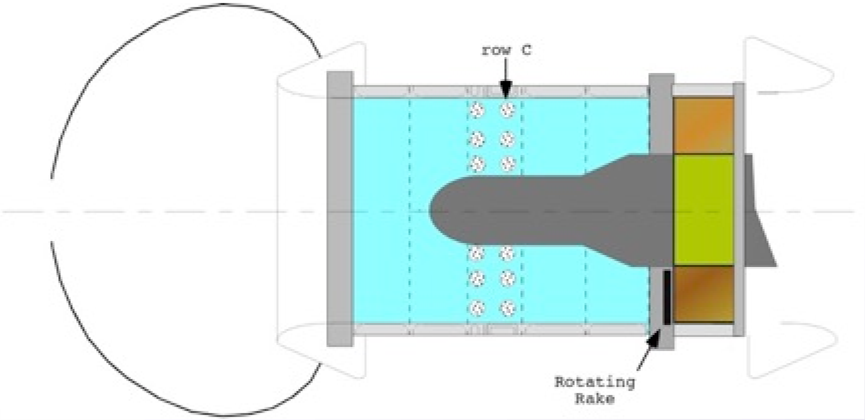
Grumman Liners: Three test barrels were fabricated for the ANC test program. The impedance of each of these barrels are described in the contractor report.

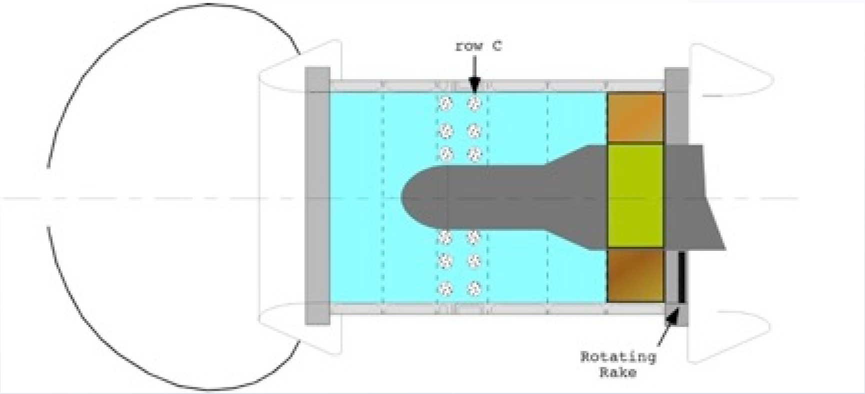
Foam Metal Liner
SRF Liner (with instrumentation)

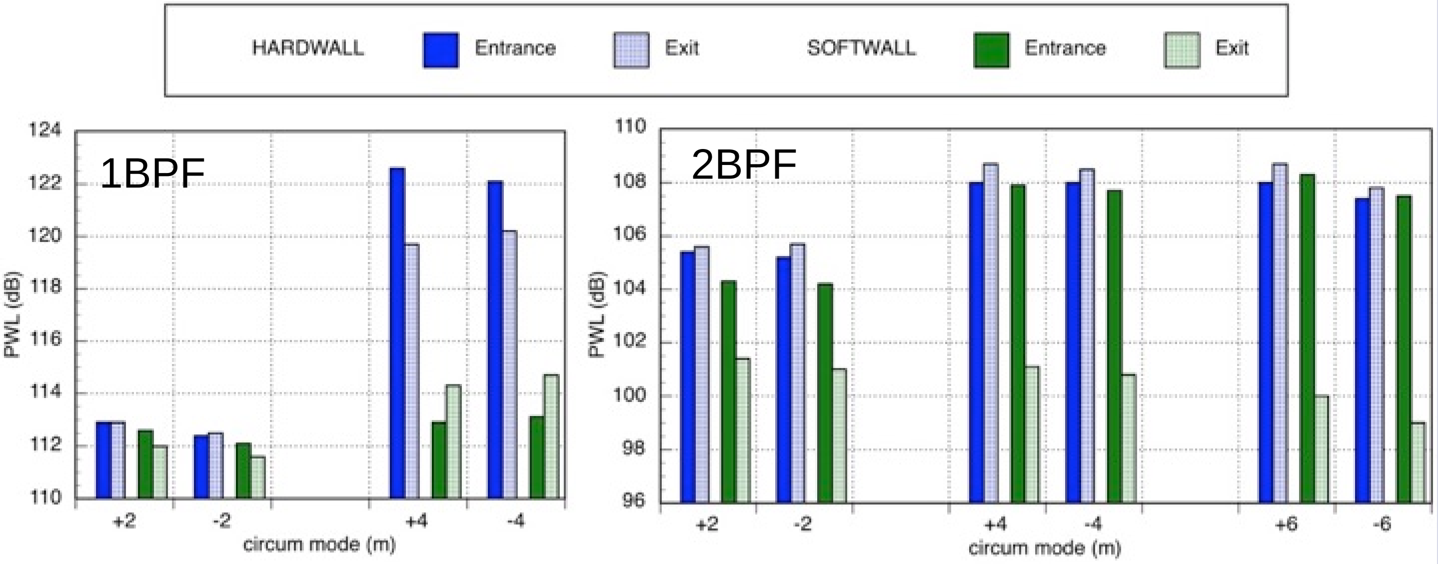


Liner Insertion Loss

Compare PWLs with rake installed at entrance of liner to installation at exit of liner.





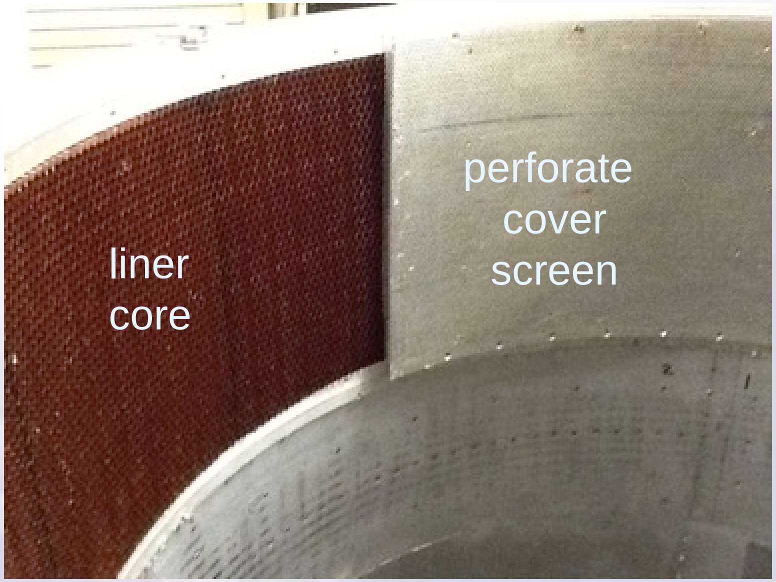


Liner Build-Up

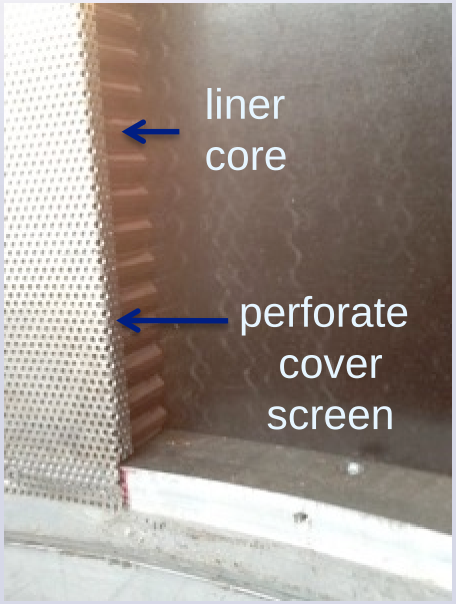
Hexcel manufactured core at their facility according to NASA LaRC/GRC specification at no cost.

Assembly of liner at GRC with LaRC and Hexcel providing expertise.

Strong partnership created that will have positive impact for continued TRL advancement.



Close up of liner – partially exposed

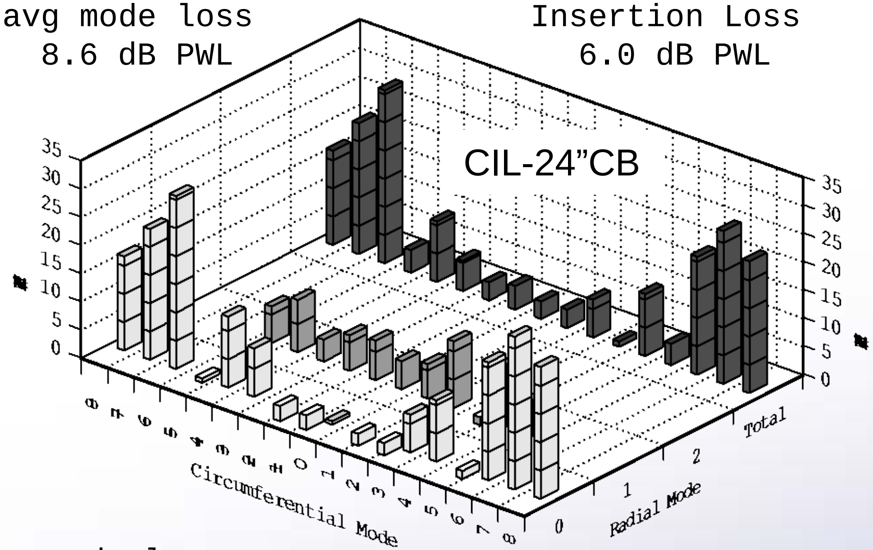


Close up of liner cross-section

In-Duct Acoustic Results

avg mode loss
8.6 dB PWL

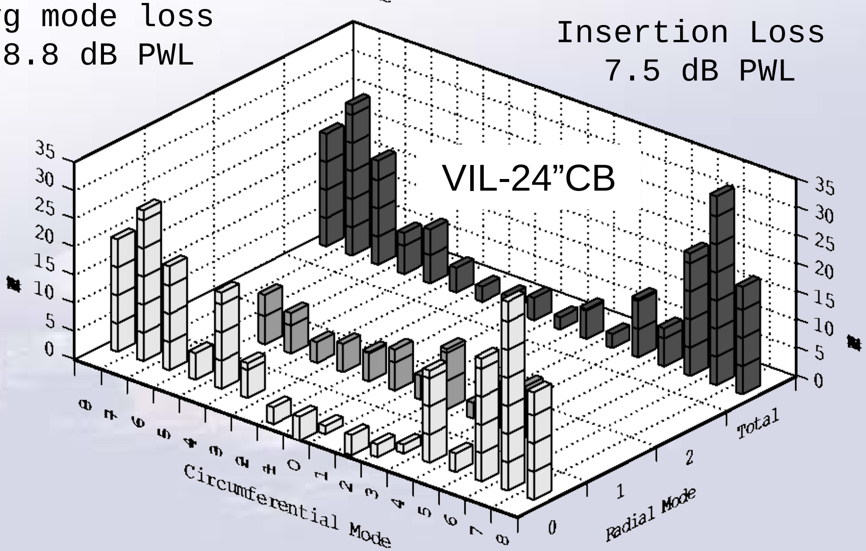
Insertion Loss
6.0 dB PWL



Vertical Orientation
CFANS * 900 Hz
Random Mode Excitation

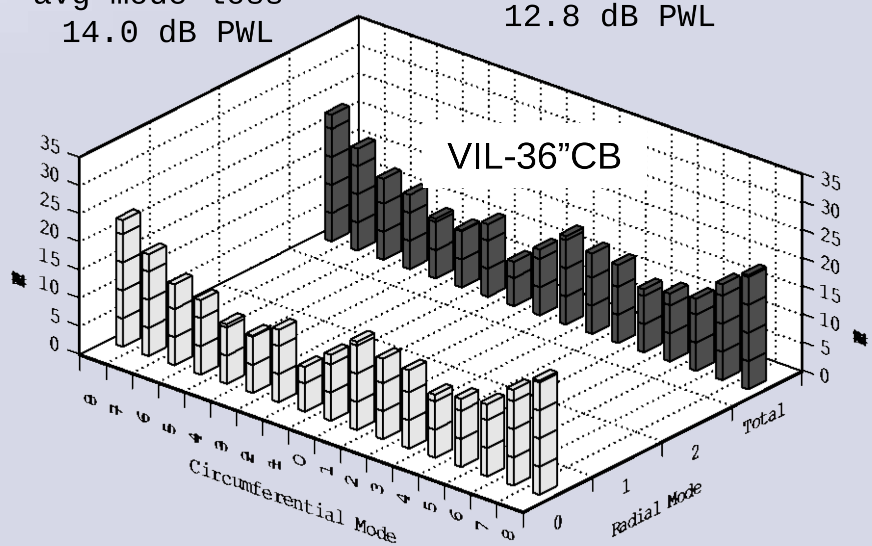
avg mode loss
8.8 dB PWL

Insertion Loss
7.5 dB PWL

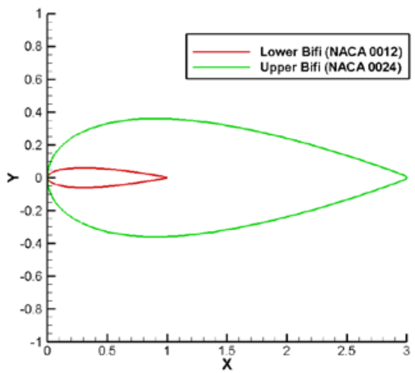


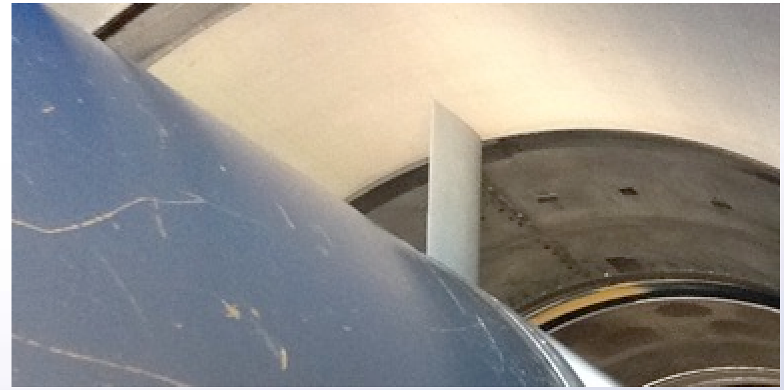
avg mode loss
14.0 dB PWL

Insertion Loss
12.8 dB PWL



Liner w/ Pylons - Reflections





Large	Large
Both	Both

2.4

2.2

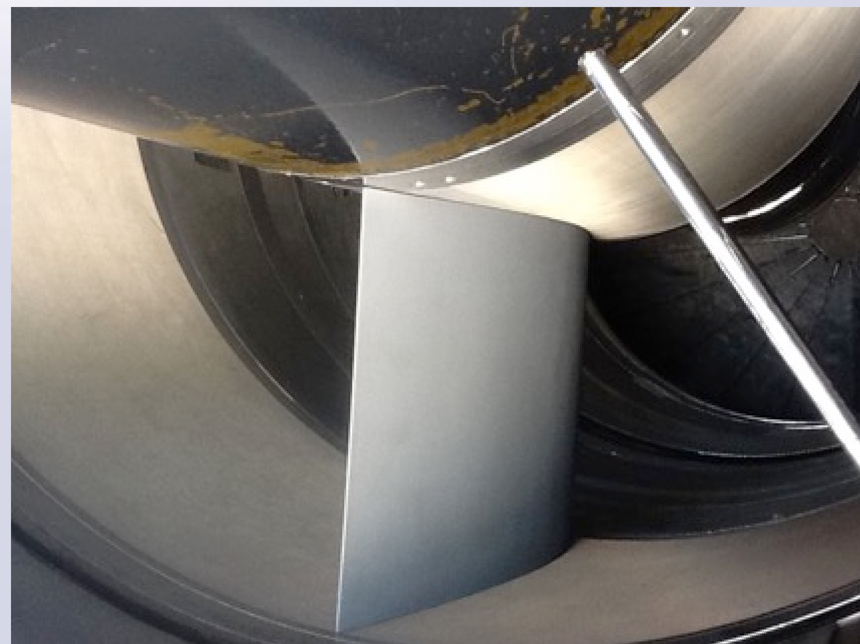
.8

0.6

0.4

1xBPF

-0.5

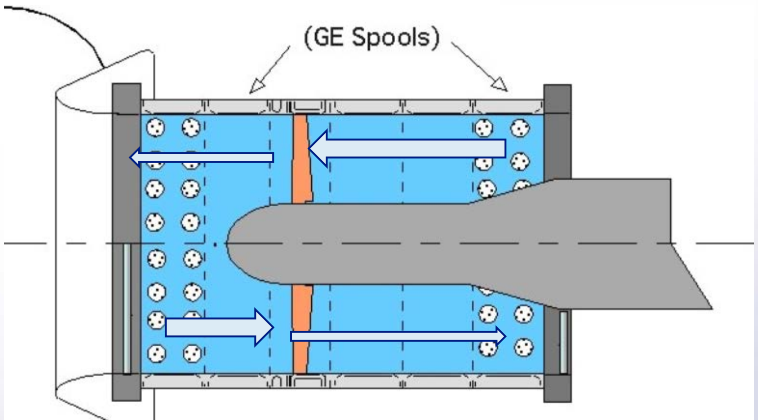


Mode Blockage / Transmission

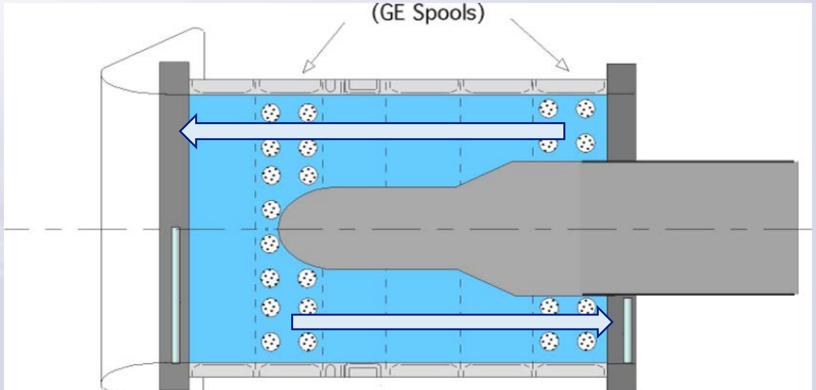
Assume modes generated by CFANS in clean configuration are consistent. Implicit assumption is the mode source does not change w/ ~0.15 M#.

Add blockage in the form of stators at several different pitches & counts. (14/28V @ 20° /45°)

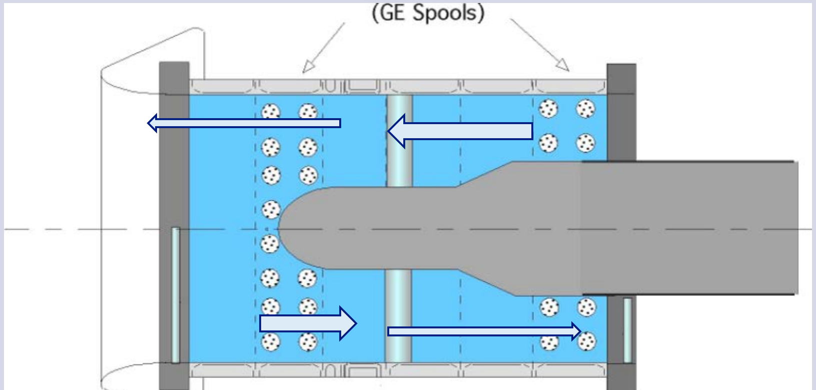
Add blockage in the form of rotor alone at several different pitches & rpms. (18° /28° /38°)
(de-sync the rake & the fan by ~1%)
Measure transmitted mode.



Rotor Blockage



Unblocked

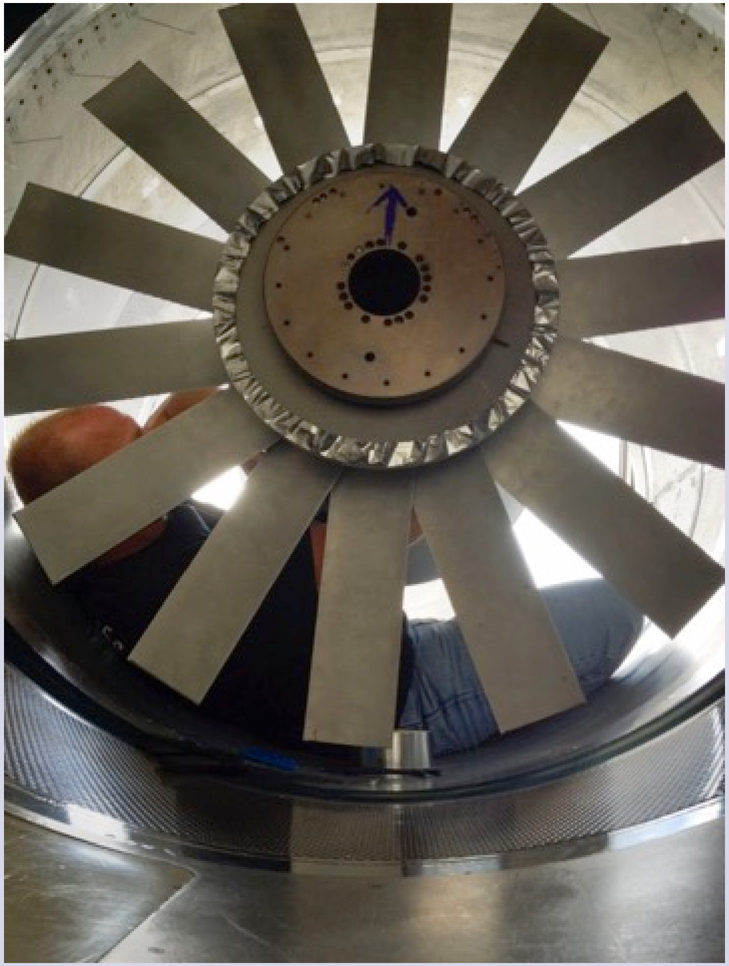


Stator Blockage

Mode Blockage / Transmission

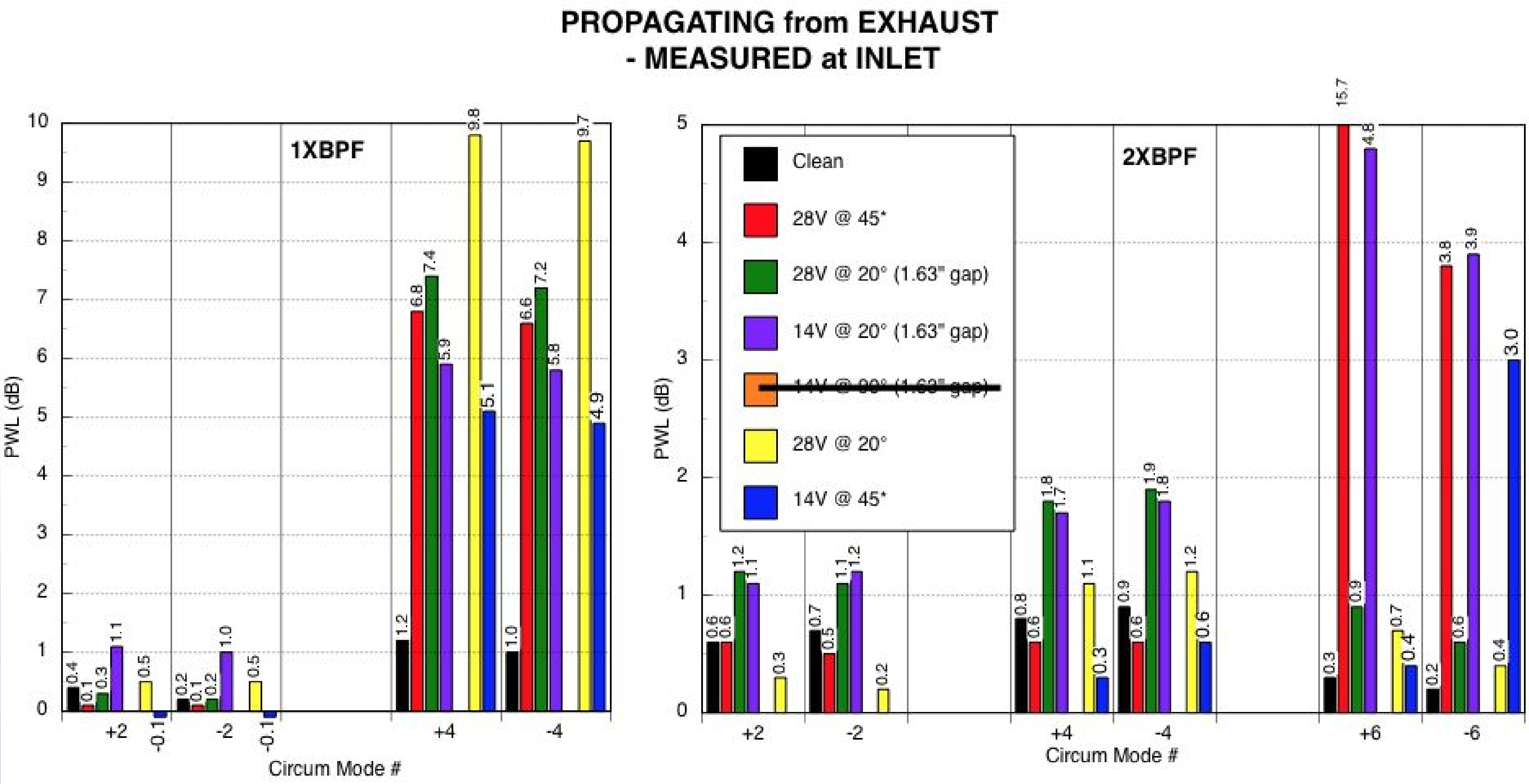
28 Vanes @ 20˚

14 Vanes @ 20˚



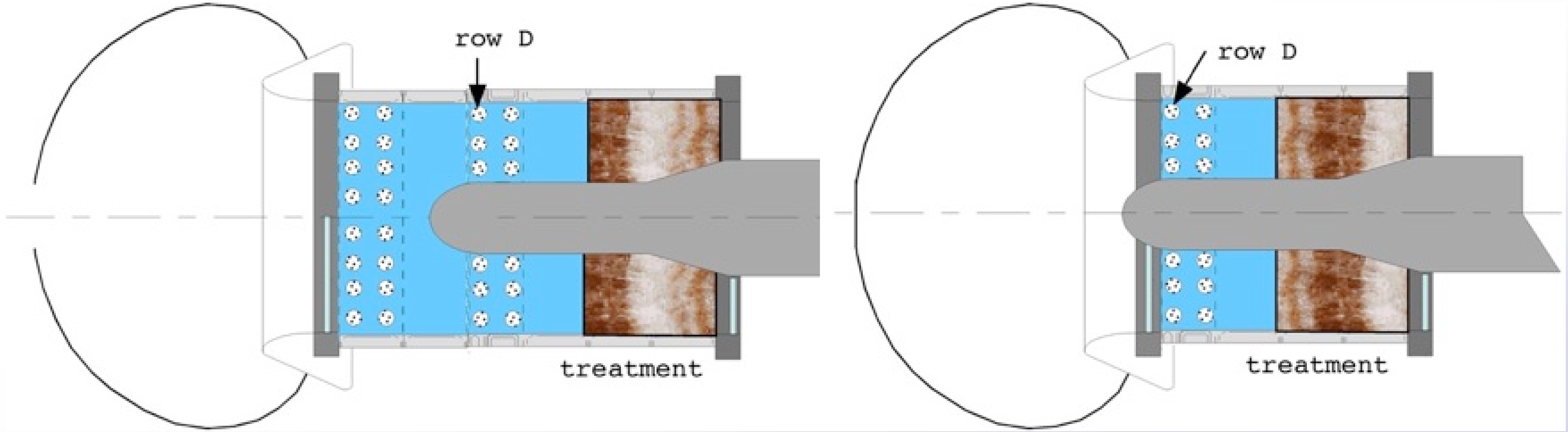
14 Vanes @ 45˚

Mode Blockage – Results (typ)



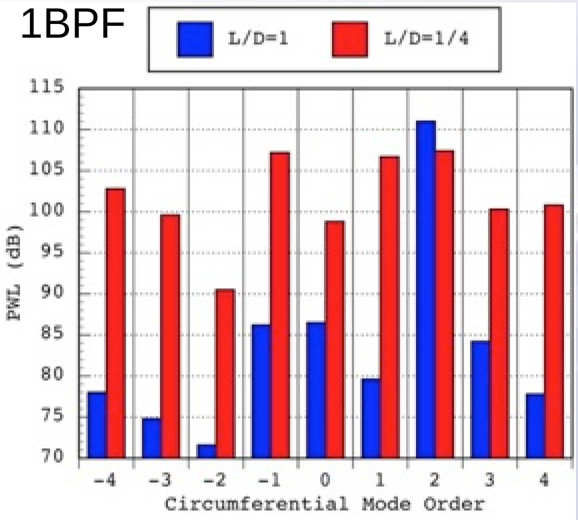
Effects of Short Duct on Acoustic Modes

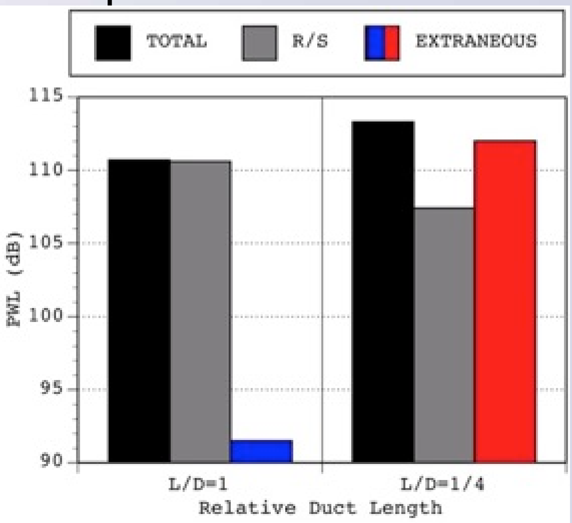
Trend in turbofan engines is shorter ducts. 'Infinite' duct theory for mode propagation & radiation to farfield may not be valid. Need to obtain database for code validation.

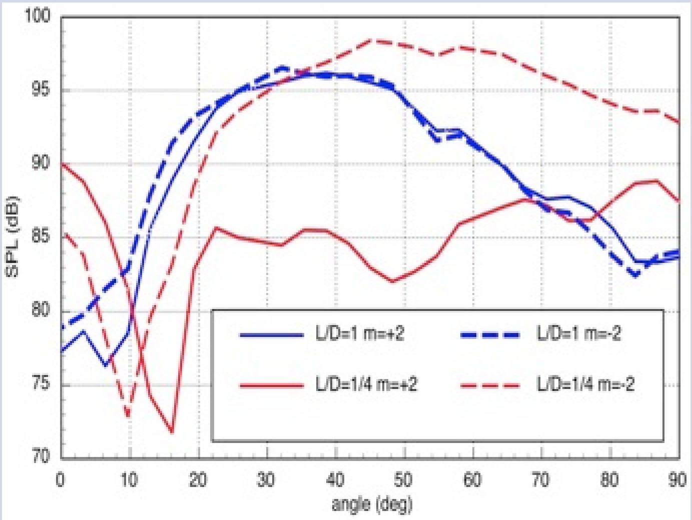


Compare PWLs with L/D =1 to 1/4.

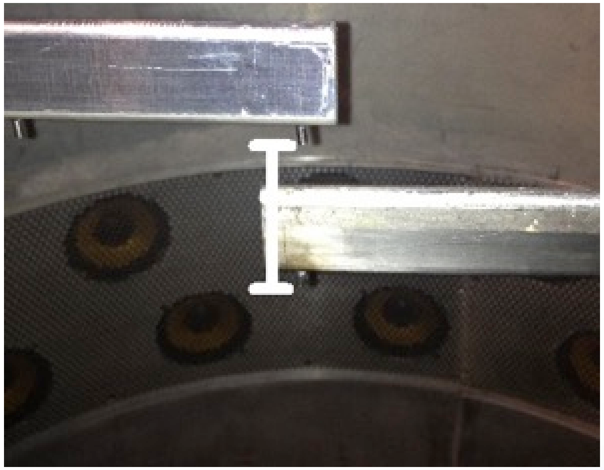
1BPF

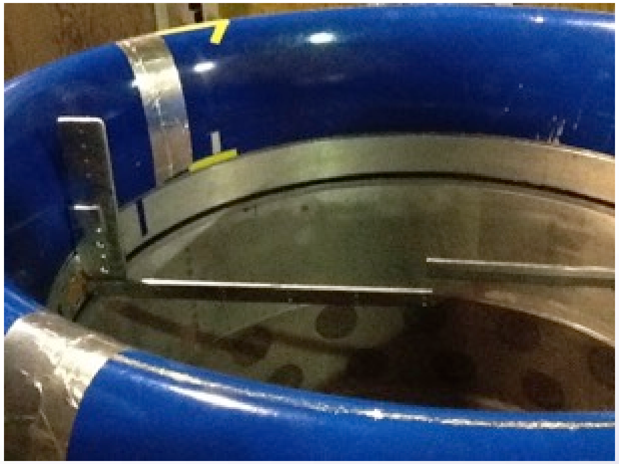






Mode Reflection





Rotating Rake measures at a single axial location.

Measures the superposition of the forward propagating and reflected wave.

Identified as a concern in 1995 as a follow on report to the original ADP rotating rake 9x15/UHB entry - Cicon, et. al, NASA CR (12 dB error).

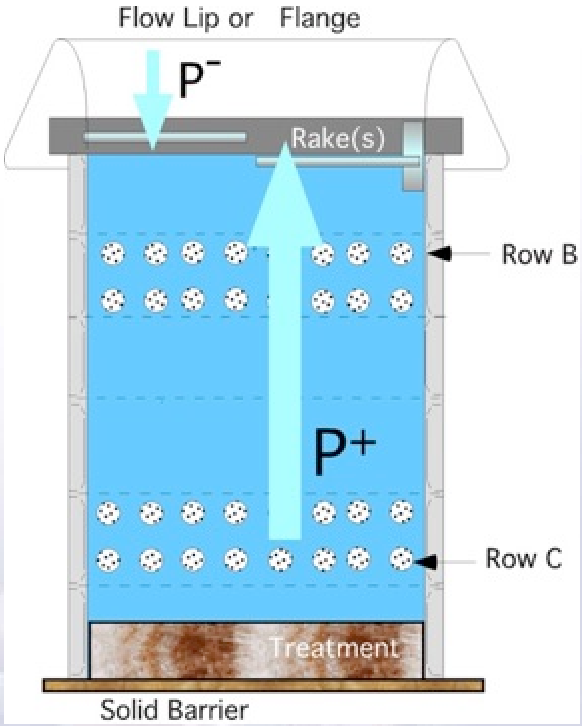
Developing a dual-rake technique to separate forward propagating and reflected wave.

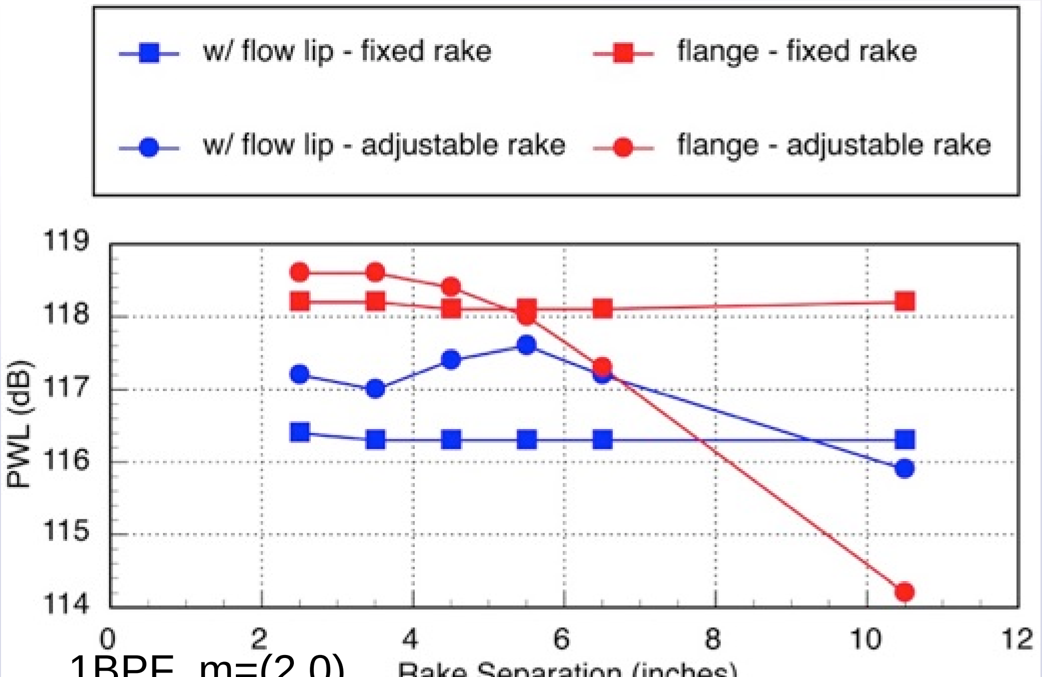
Detail: Dahl, et. al.

Mode Reflection

Database set for natural inlet reflections –

minimal with flow lip; exaggerated w/ flange





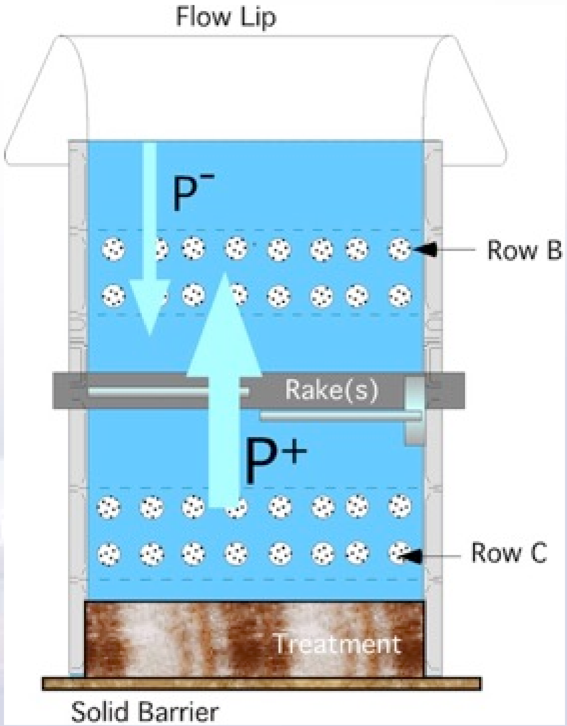
1BPF m=(2,0)

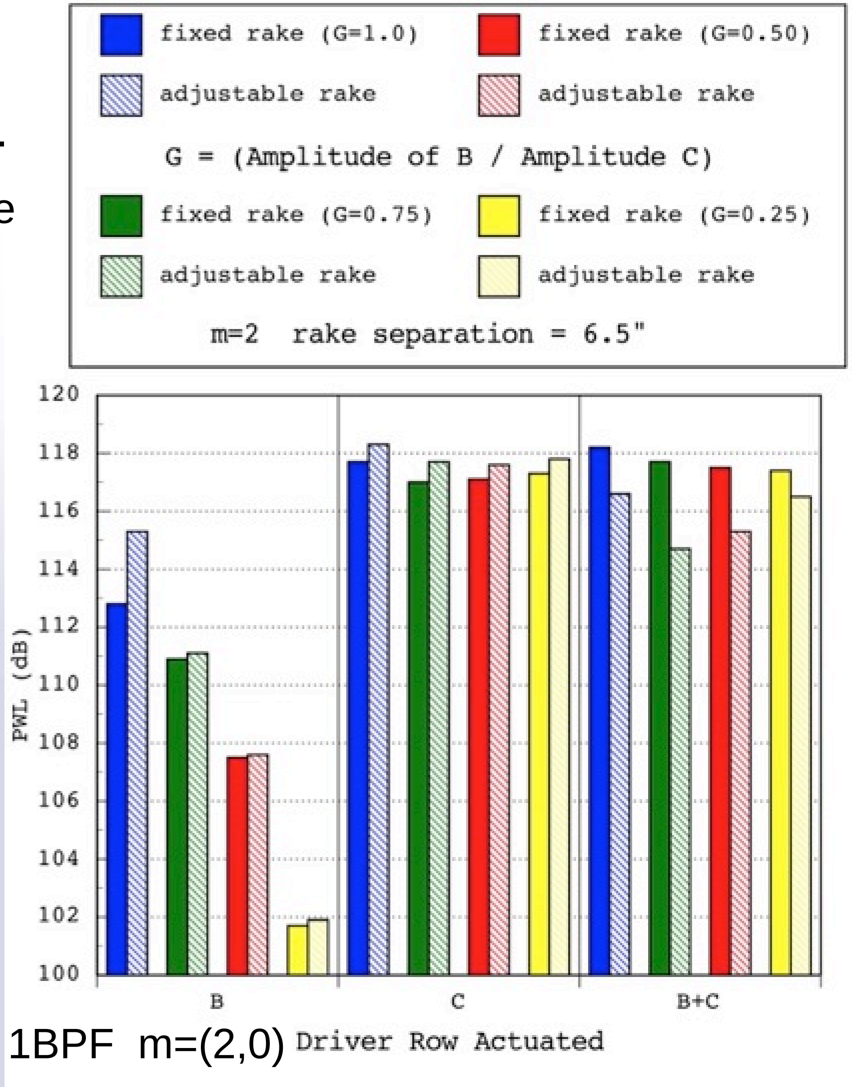
Mode Reflection

Database set for artificially created forward propagating and reflected waves –

Run driver sets independently, then simultaneously.

Assumption is that this experimentally measures the propagating and reflected waves , and the superposition is linear.





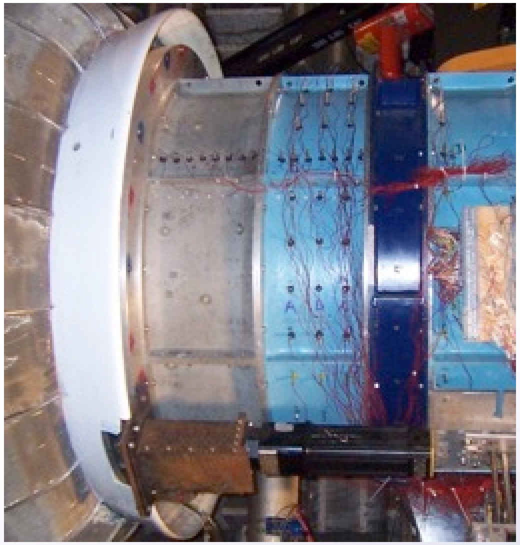
ASSUMPTION: $P^{+}_{alone}, P^{-}_{alone} = P^{+}_{simultaneous}, P^{-}_{simultaneous}$

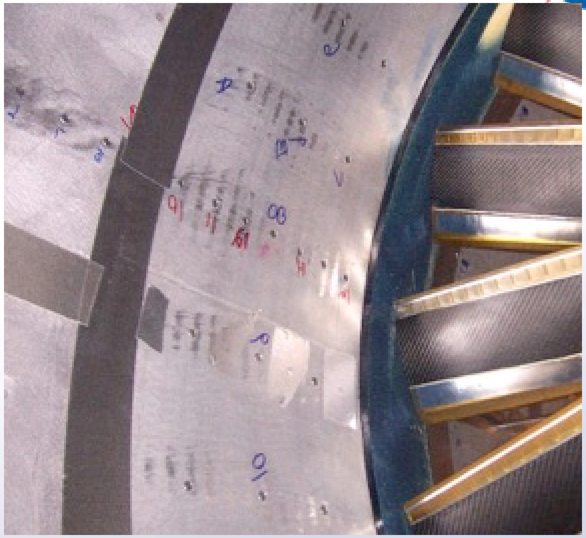
MEASUREMENT TECHNOLOGIES EVALUATED

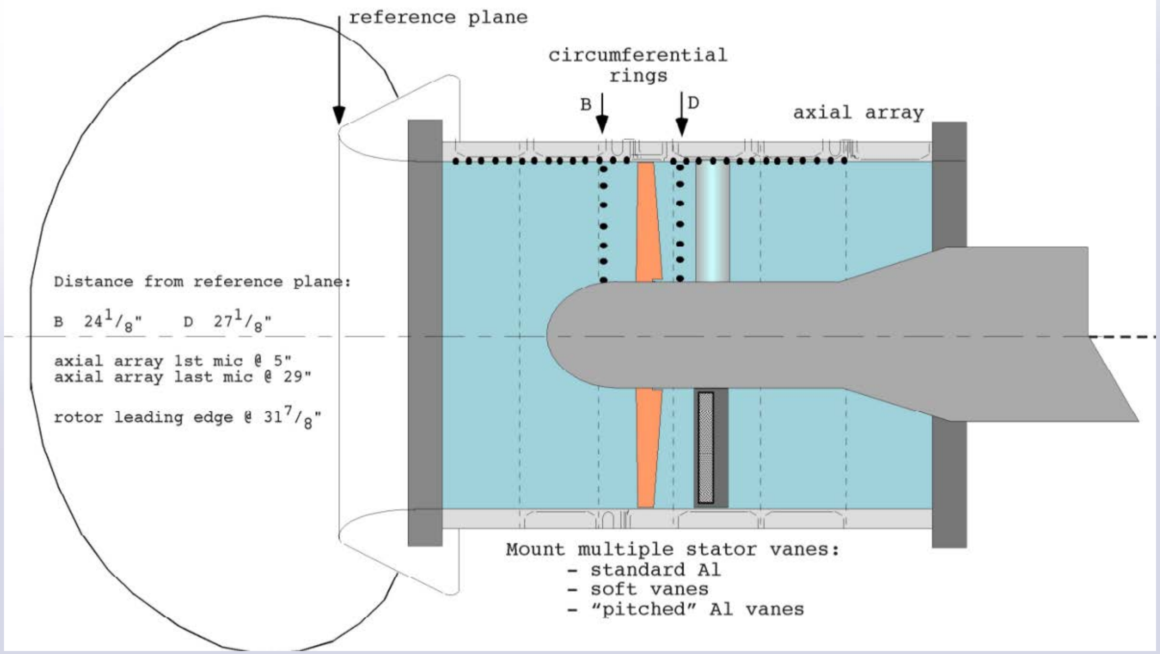
In-Duct Array

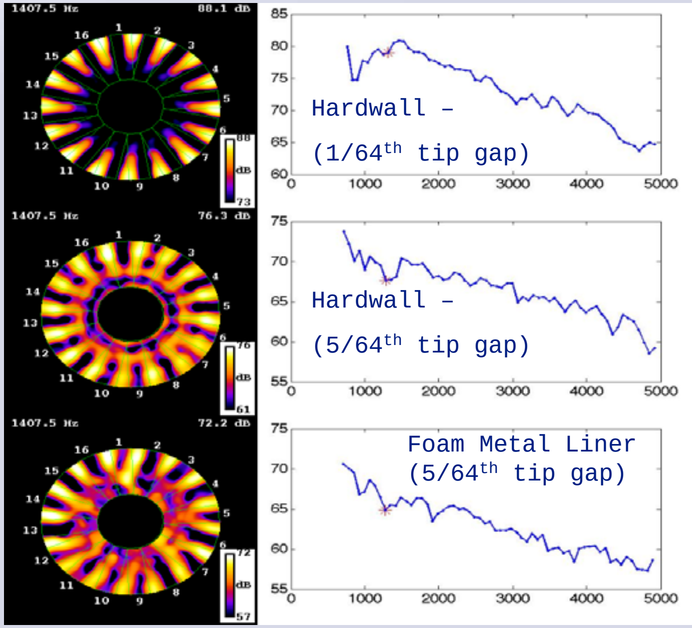
Advance in-duct imaging system

- higher frequency/combined rotating & stationary sources
- MOTU for transferable system



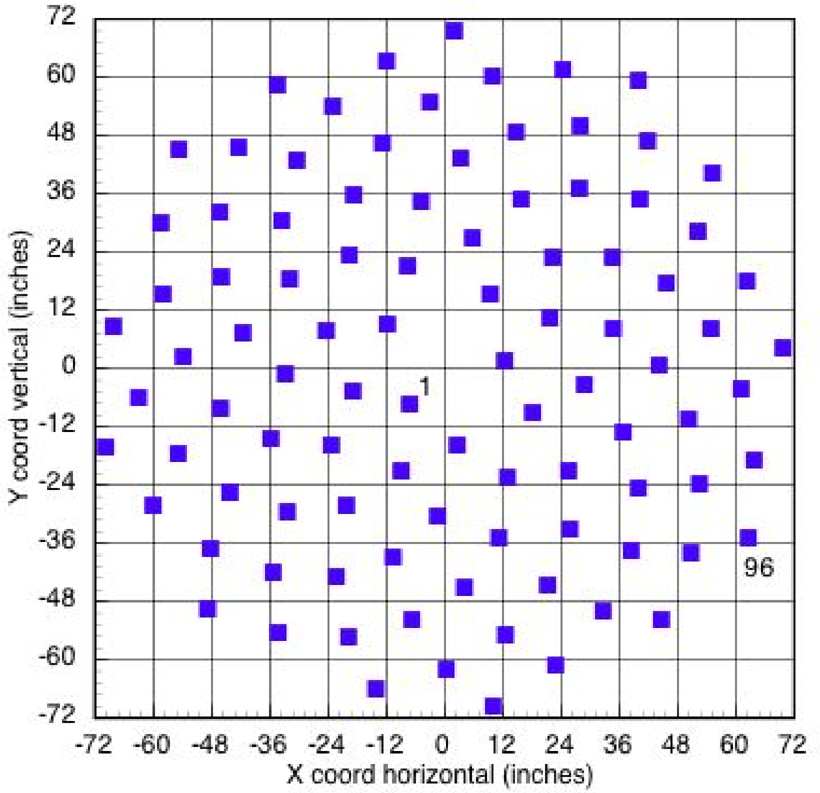






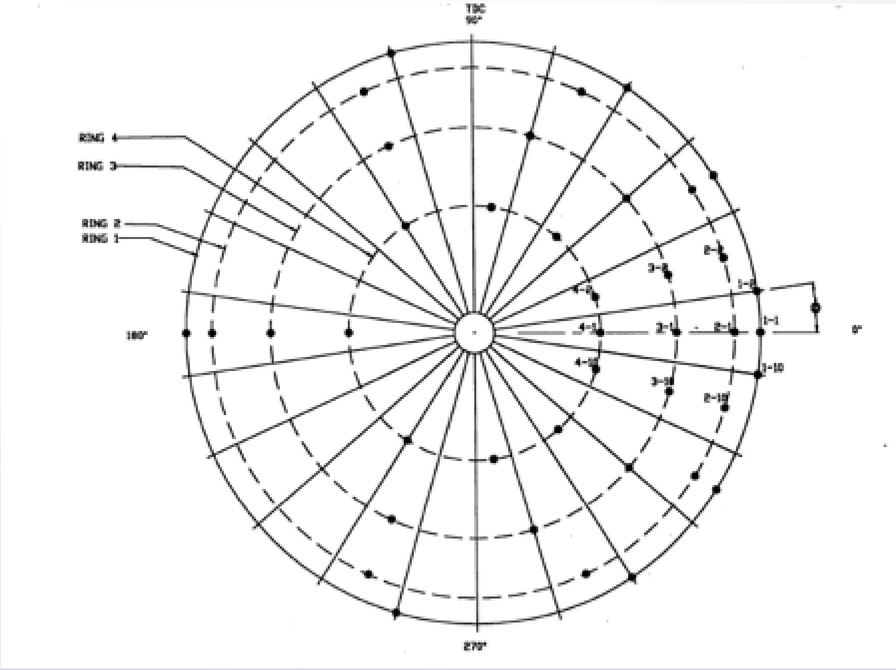
Array 96 - Setup

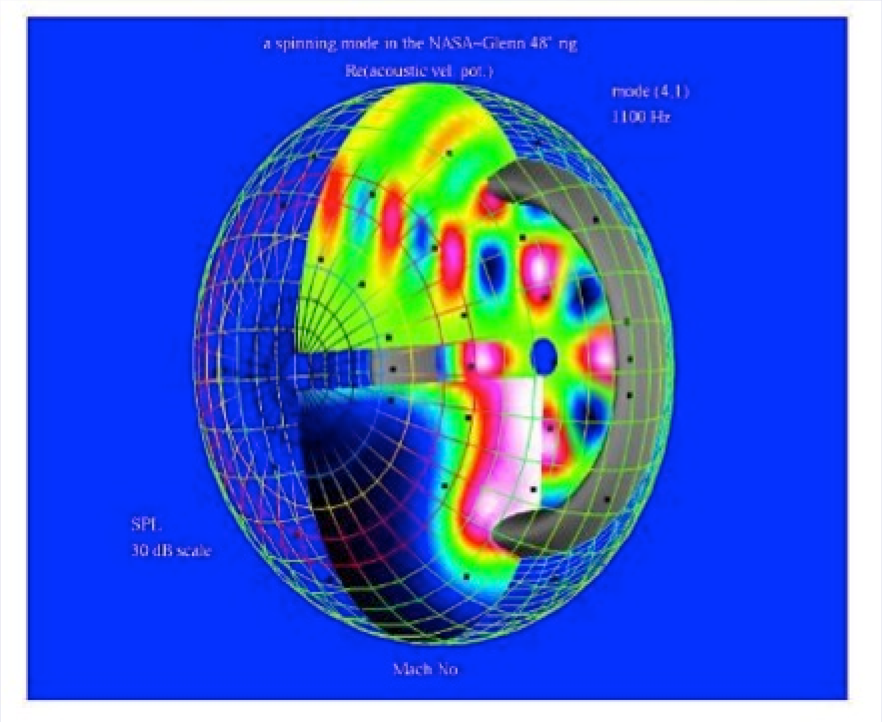
Standing behind the array (facing the array and, beyond it, the ICD and the ANCF



ICD Array

Use ICD surface for acoustic measurement
(especially useful in static engine testing)
Compare to 'gold standard' :
Rotating Rake / Farfield





CONCLUSION

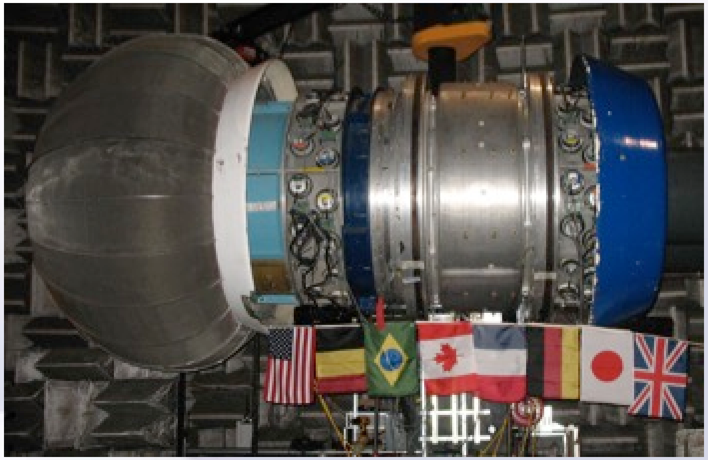
ANCF - Summary

Design, test, and evaluation for technical risk-mitigation of most of the innovative fan noise reduction technologies developed by NASA over the past 20 years.

1992 – 2015 : Low-TRL research performed on ANCF enabled the advancement of multiple noise reduction and measurement technologies.

The ANCF has been used in over 6 internal, 8 external programs (2 reimbursable), 2 NRAs, 3 SBIRs, and 2 Aero Acoustic Research Consortium programs. These were integrated in GRC's noise reduction program milestones. It is the only complete aero-acoustic data/geometry set publically available.

Over 100 papers written based on ANCF data. (~4 -6 per AIAA Aero-Acoustics Conference)



- Highly flexible, fundamental test bed.
- Multiple configurations, including rotor alone.
- 4-foot diameter ducted fan
- Low speed: (variable)
  - ~1800 rpm, V_{tip} ~375 ft/sec, M_{duct} ~ 0.15
- Used to provide aero-acoustic database and to evaluate noise reduction technologies

Databases requested & utilized for IR&D by:

GEAC / GECR
Honeywell
Goodrich
Pratt & Whitney
EXA, Inc
Embraer, Inc
NUMECA
ONERA

VPI/Techsburg
Illinois State University
U of Cincinnati
The OSU

University of Sherbrooke
Federal University of Brazil
University of Sao Paulo

2016+ : Proposed funding structure not supporting low-TRL fan acoustic research needed to enable meeting project goals.

Investigating transferring the ANCF to a university to jointly operate the ANCF to maintain research capability, and provide relevant STEM opportunities, in the area of fan acoustics.

References

- **ANCF DESCRIPTION:**

“Artificial Noise Systems for Parametric Studies of Turbo-machinery Aero-acoustics”, International Journal of Aeroacoustics, DLS and BE Walker (to be published 2016).

“A Mode Propagation Database Suitable for Code Validation Utilizing the NASA Glenn Advanced Noise Control Fan and Artificial Sources”, AIAA 2014-0719, DLS

“The Advanced Noise Control Fan Baseline Measurements”, AIAA-2009-0624, J McAllister, RA Loew, JT Lauer, & DLS.

“The Advanced Noise Control Fan”, AIAA-2006-3150, RA Loew, JT Lauer, J McAllister, & DLS.

- **SIGNIFICANT NOISE REDUCTION TECHNOLOGIES:**

“Low-Speed Fan Noise Attenuation from a Foam-Metal Liner”, AIAA Journal of Aircraft, July-Aug 2009, DLS and M.G. Jones.

“Low-Speed Fan Noise Reduction with Trailing Edge Blowing”, International Journal of Aeroacoustics, 2002, Vol 1 No 3, DLS, EB Fite, E Envia, & DL Tweedt.

- **ROTATING RAKE:**

“Rotating Rake Turbofan Duct Mode Measurement System”, International Journal of Aeroacoustics, June 2007, DLS.